On the Exotic String Landscape

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Based on: 2309.15152 with Yuta Hamada, Kaan Baykara, Cumrun Vafa

+ work in progress

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String Landscape

Geometric string constructions do lots of the heavy lifting!

Geometric **String Landscape**


String Landscape
Geometric
Non-geometric
M9
E_8
M5
M2
M2
M2
M9
E_8
M5


Geometric
String Landscape
Today
Non-geometric
M9
M5
M2
M2
M2
M9
M5

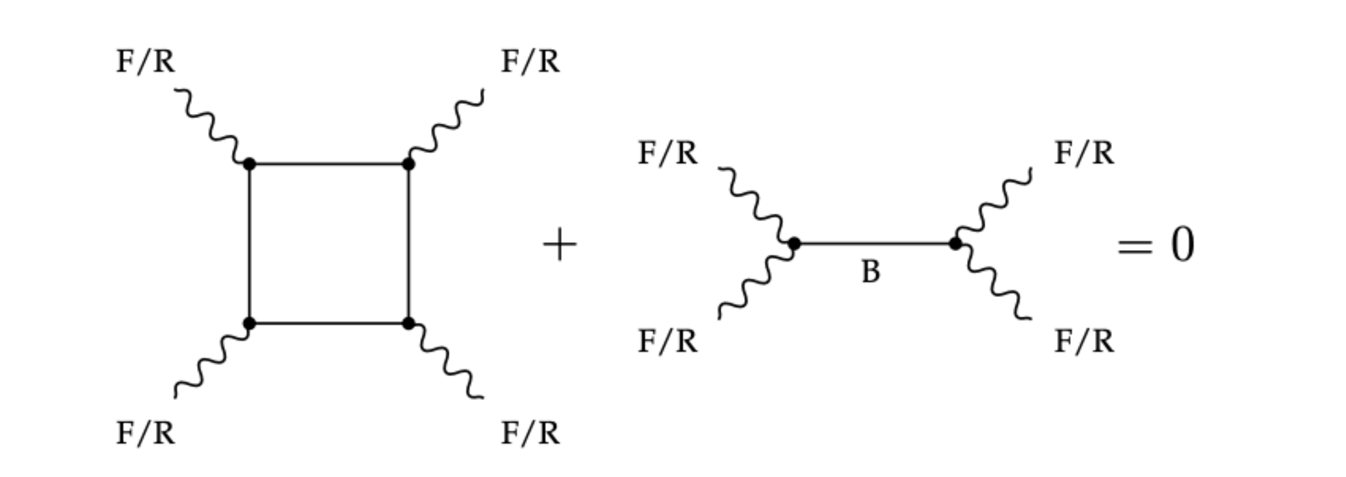

String Landscape
Geometric
Today
Connections?
Non-geometric
M9
M5
M2

6d $\mathcal{N} = 1$ Supergravity theories

Super-multiplets:

Supergravity-multiplet	$(g_{\mu\nu}, B_{\mu\nu}, \psi^-_\mu)$
Tensor-multiplet(T)	$(B_{\mu\nu}, \phi, \chi^+)$
Vector-multiplet(V)	(A_μ, λ^-)
Hyper-multiplet(H)	$(4h, \psi^+)$

Chiral fields contribute to gauge/gravitational anomalies
Cancelled by the **Green-Schwarz-Sagnotti Mechanism**



Anomaly polynomial factorizes as:

$$I_8 = \frac{1}{2}\Omega_{\alpha\beta}X_4^\alpha X_4^\beta$$

$$X^\alpha = \frac{1}{2}a^\alpha trR^2 + \sum_i b_i^\alpha\left(\frac{2}{\lambda_i}trF_i^2\right)$$

$\Omega_{\alpha\beta}$ symmetric of signature (1,T)

$a^\alpha, b_i^\alpha \in \mathbb{R}^{1,T}$

Anomaly Cancellation:

$$R^4 : \quad H - V = 273 - 29T$$

$$F^4 : \quad 0 = B^i_{Adj} - \sum n^i_R B^i_R$$

$$(R^2)^2 : \; a \cdot a = 9 - T \in \mathbb{Z}$$

$$F^2R^2 : \; a \cdot b_i = \frac{1}{6}\lambda_i\left(A^i_{Adj} - \sum_R n^i_R A^i_R\right) \in \mathbb{Z}$$

$$(F^2)^2 : \; b_i \cdot b_i = \frac{1}{3}\lambda_i^2\left(\sum_R n^i_R C^i_R - C^i_{Adj}\right) \in \mathbb{Z}$$

$$F_i^2F_j^2 : \; b_i \cdot b_j = \sum_{R,S} \lambda_i\lambda_j n^{ij}_{RS} A^i_R A^j_S \; \in \mathbb{Z}, \; i \neq j$$

A_R, B_R, C_R group theory coefficients

$$tr_R F^2 = A_R trF^2, \; tr_R F^4 = B_R trF^4 + C_R (trF^2)^2$$

$n^i_R =$ hypers in number of in R

[Taylor, Kumar, Morison,….]

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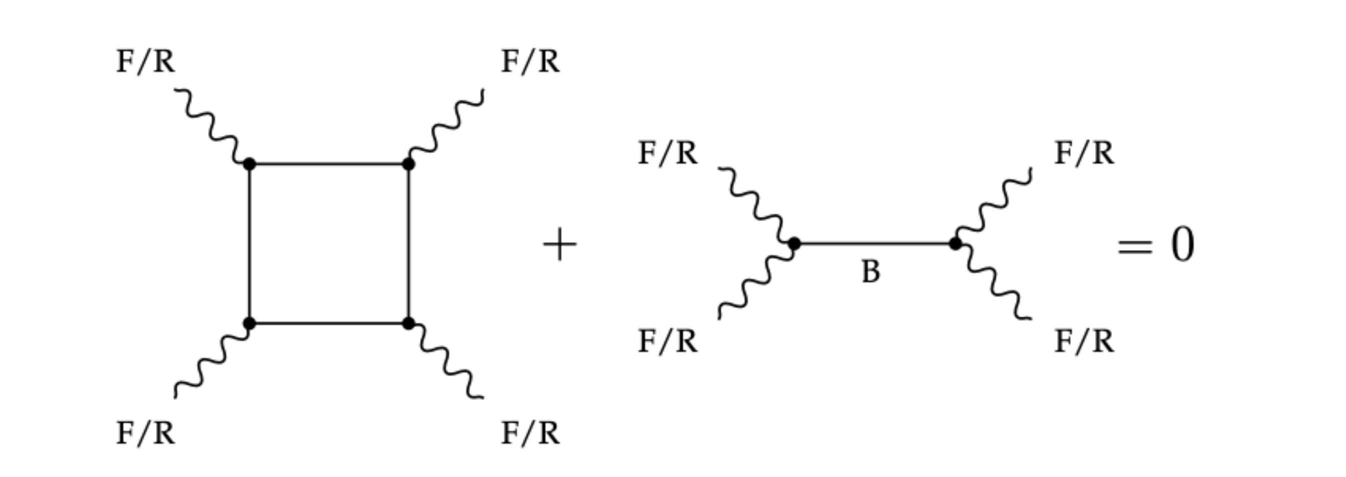

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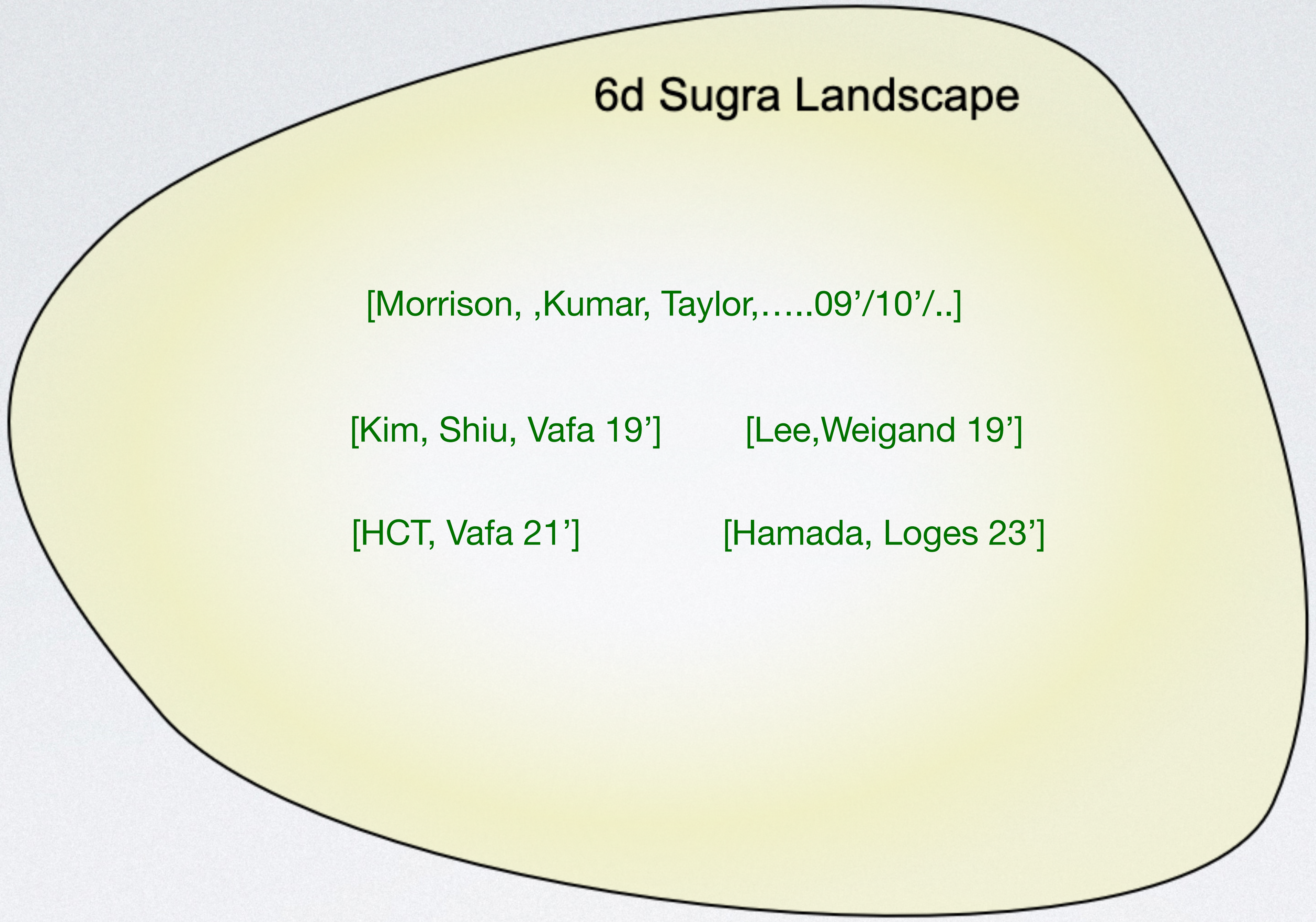
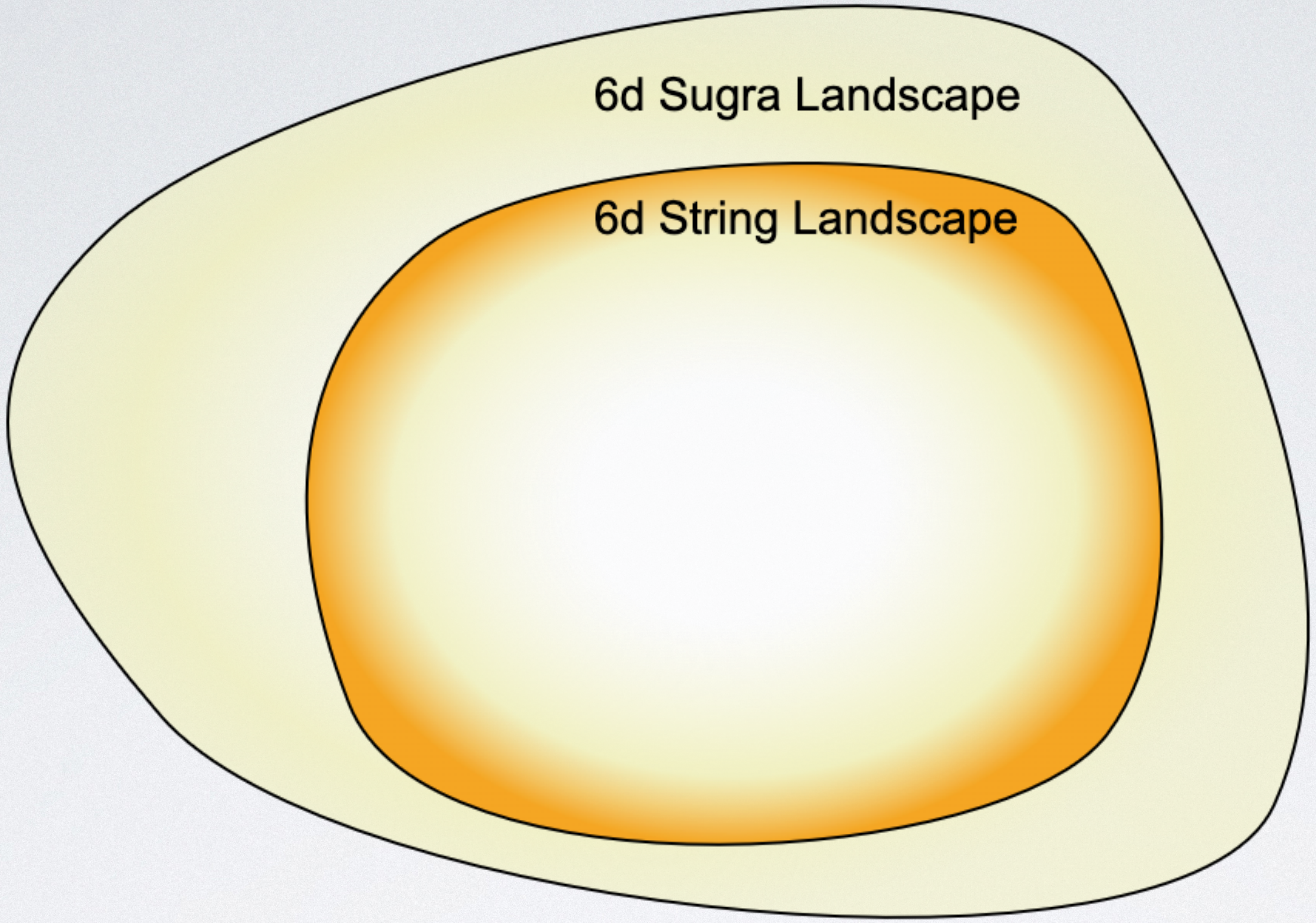
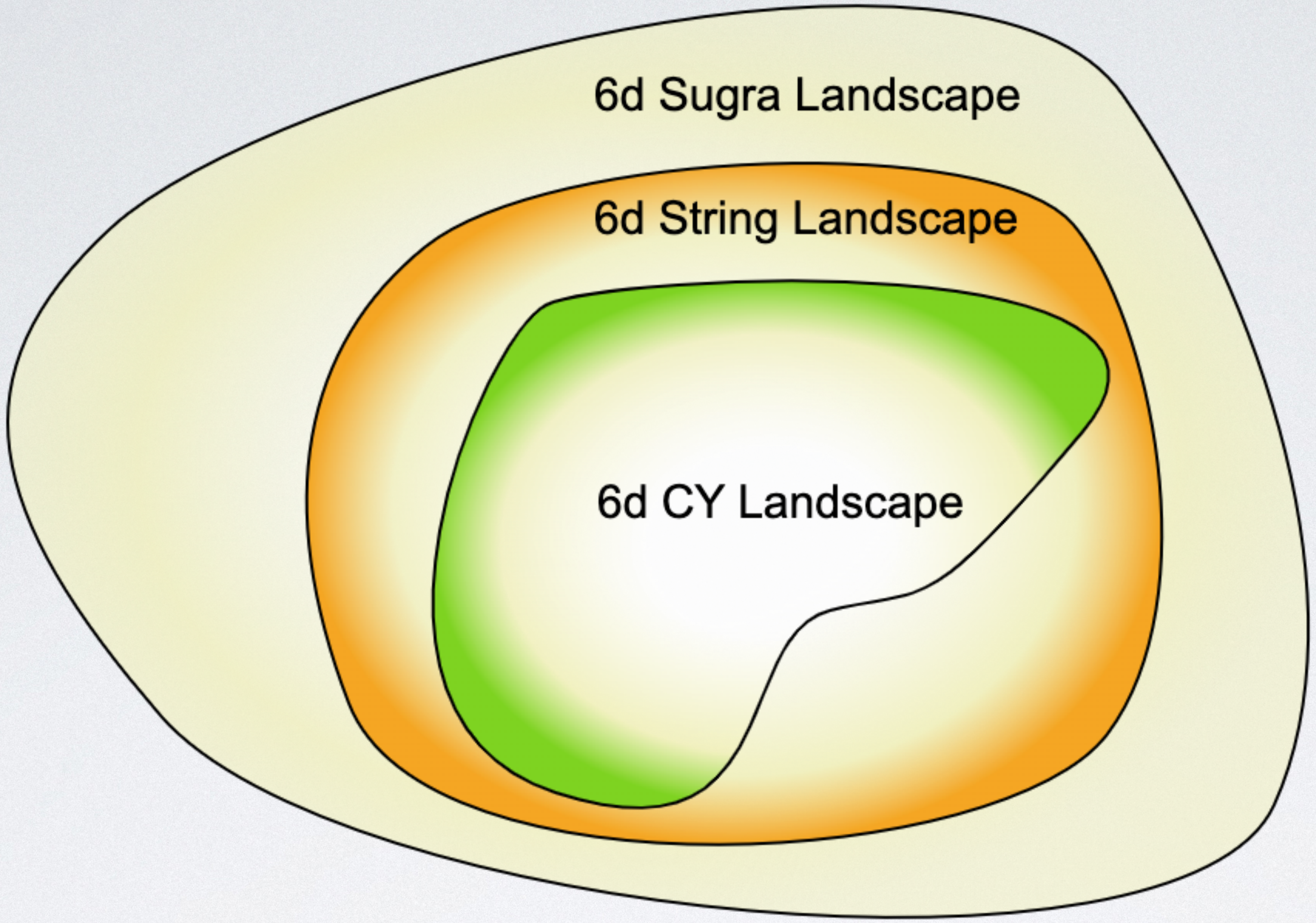
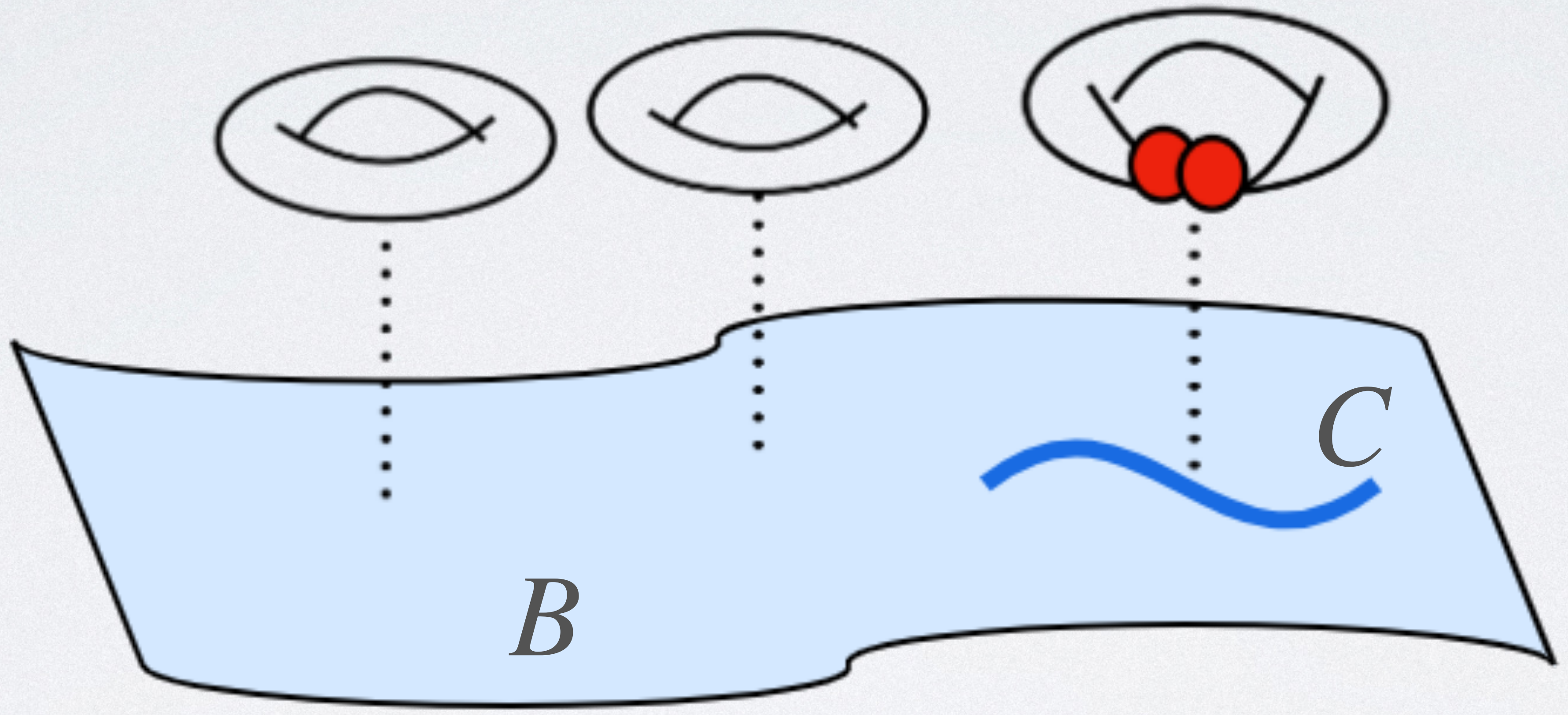

6d Sugra Landscape
[Morrison, ,Kumar, Taylor,…..09'/10'/..]
[Kim, Shiu, Vafa 19']
[Lee,Weigand 19']
[HCT, Vafa 21']
[Hamada, Loges 23']


6d Sugra Landscape
6d String Landscape


6d Sugra Landscape
6d String Landscape
6d CY Landscape

6d $\mathcal{N} = 1$ Supergravity

Large Class: F-theory on elliptic Calabi-Yau threefold



$$-a \to K_B$$

$$b \to C$$

Kodaira Condition: $$-12a = \sum_i \nu_i b_i + Y$$

6d $\mathcal{N} = 1$ Supergravity

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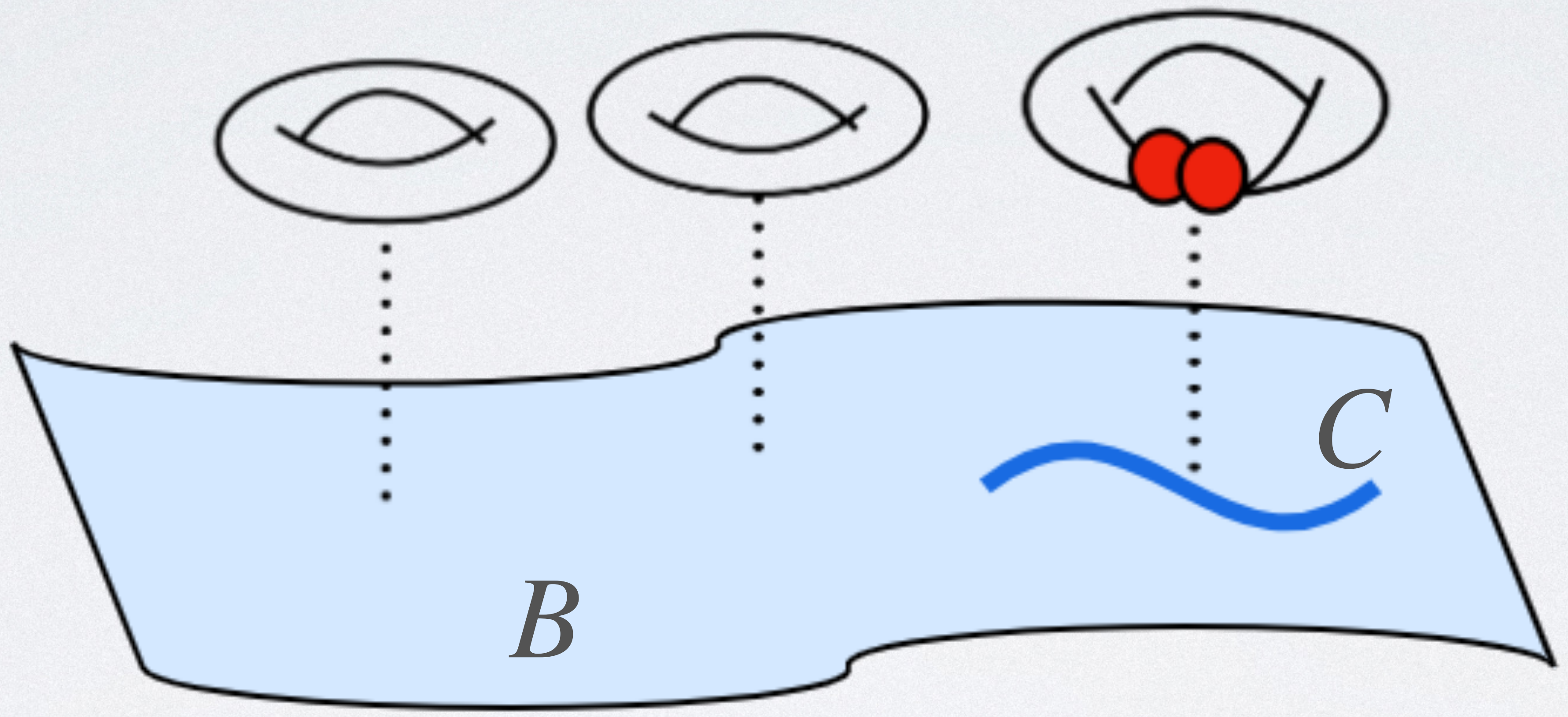


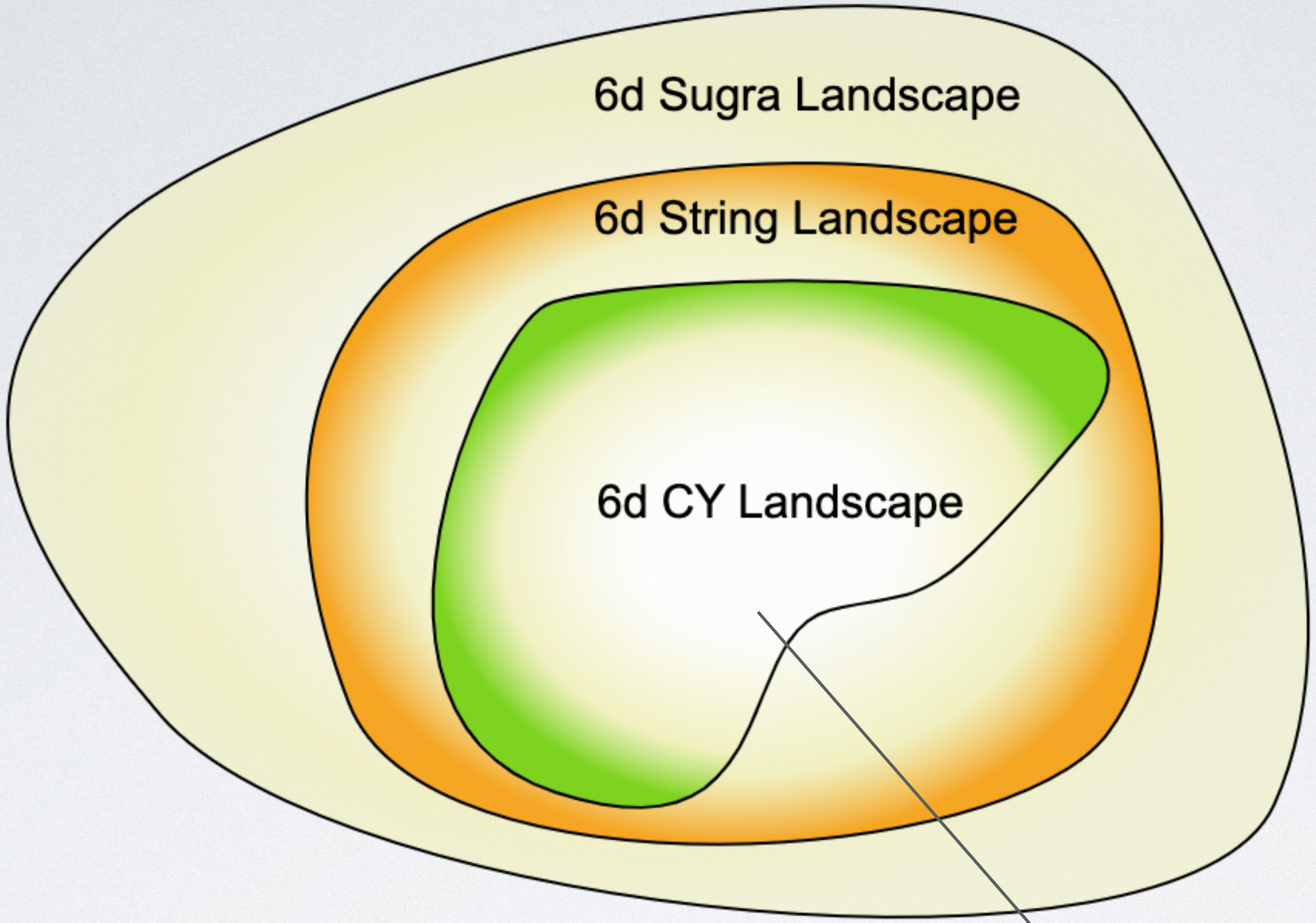
As a supergravity condition

$$B_2^a \wedge (\frac{1}{2}a^\alpha trR^2 + \sum_i b_i^a(\frac{2}{\lambda_i}trF_i^2))$$

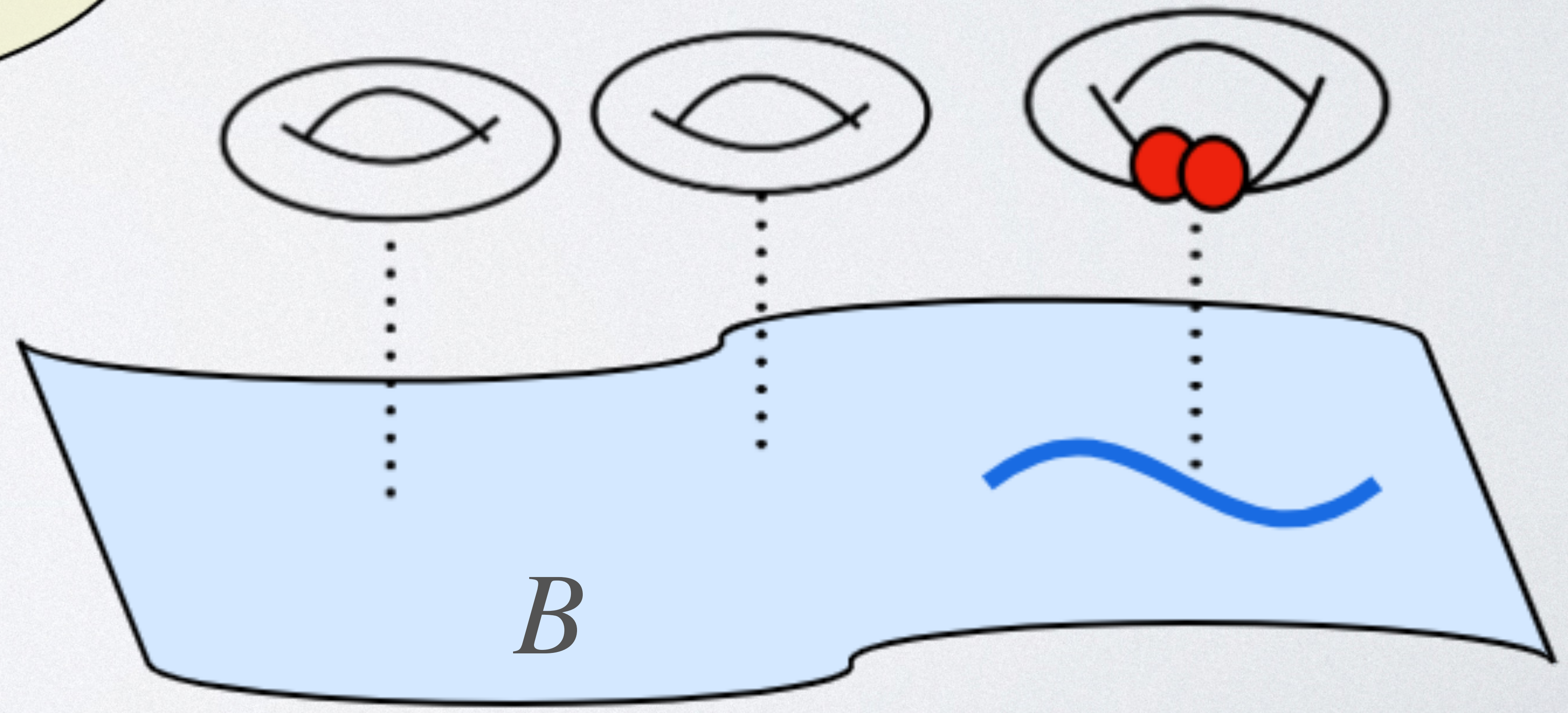
$-a \rightarrow K_B$ ⟵ Gravitational Instanton charge

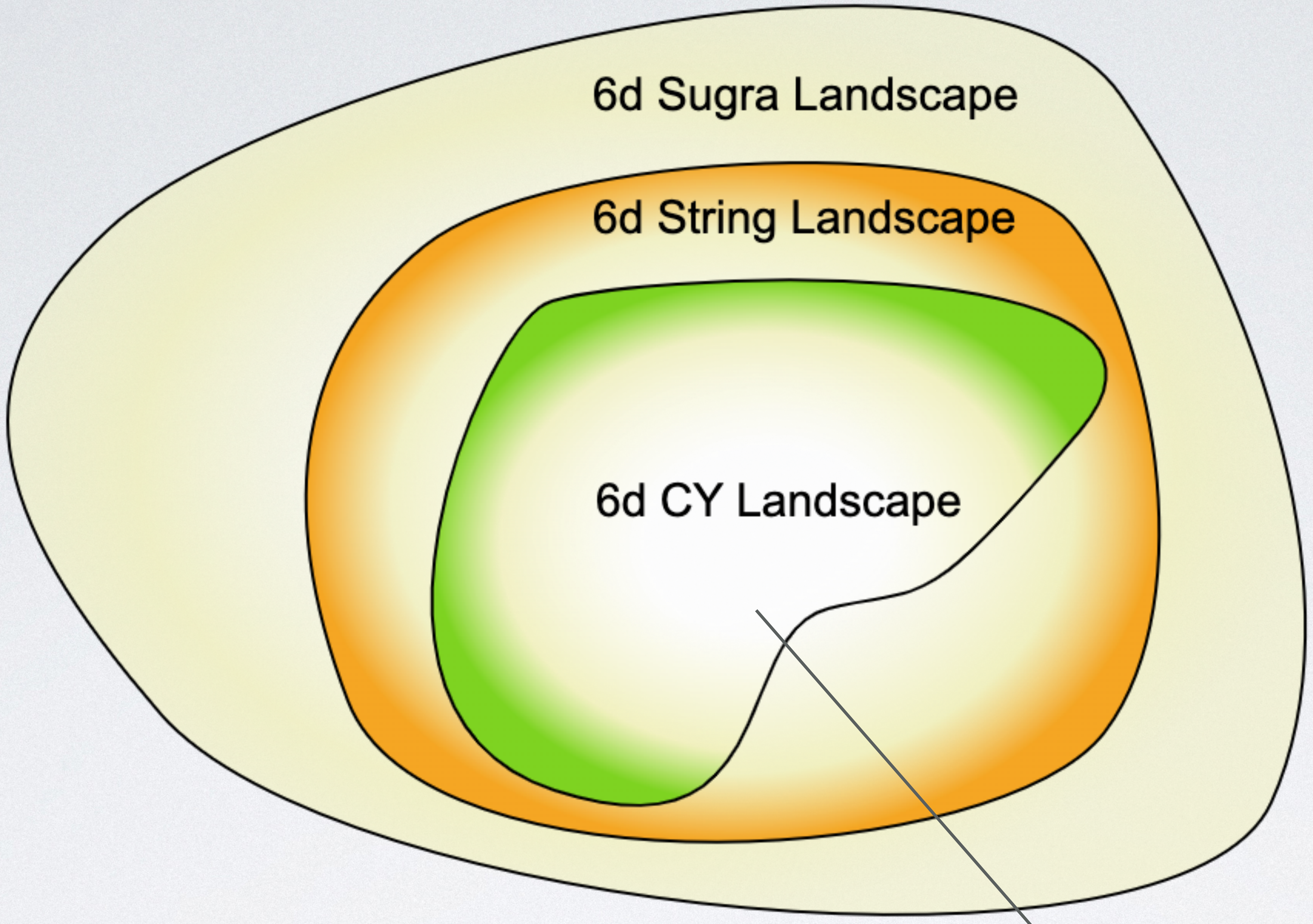
$b \rightarrow C$ ⟵ Gauge Instanton charge

Kodaira Condition: $$-12a = \sum_i \nu_i b_i + Y \xrightarrow[J \cdot Y \geq 0]{} 12\, J \cdot \underset{T_{-a}}{a} \geq \sum_i \nu_i\, J \cdot \underset{T_{b_i}}{b_i}$$



"Universal" Hypermultiplet: $Vol(B)$





What is special about the "universal" hyper?

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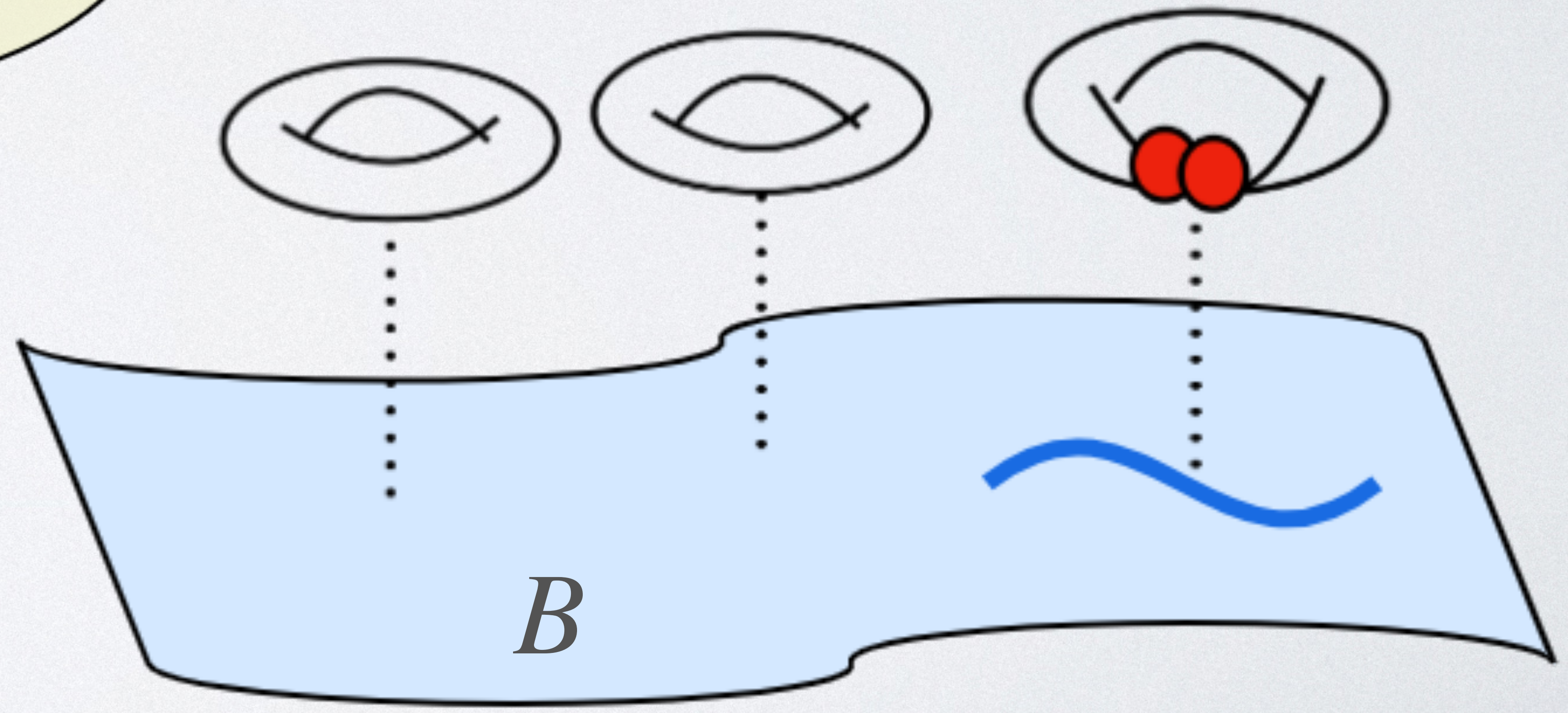

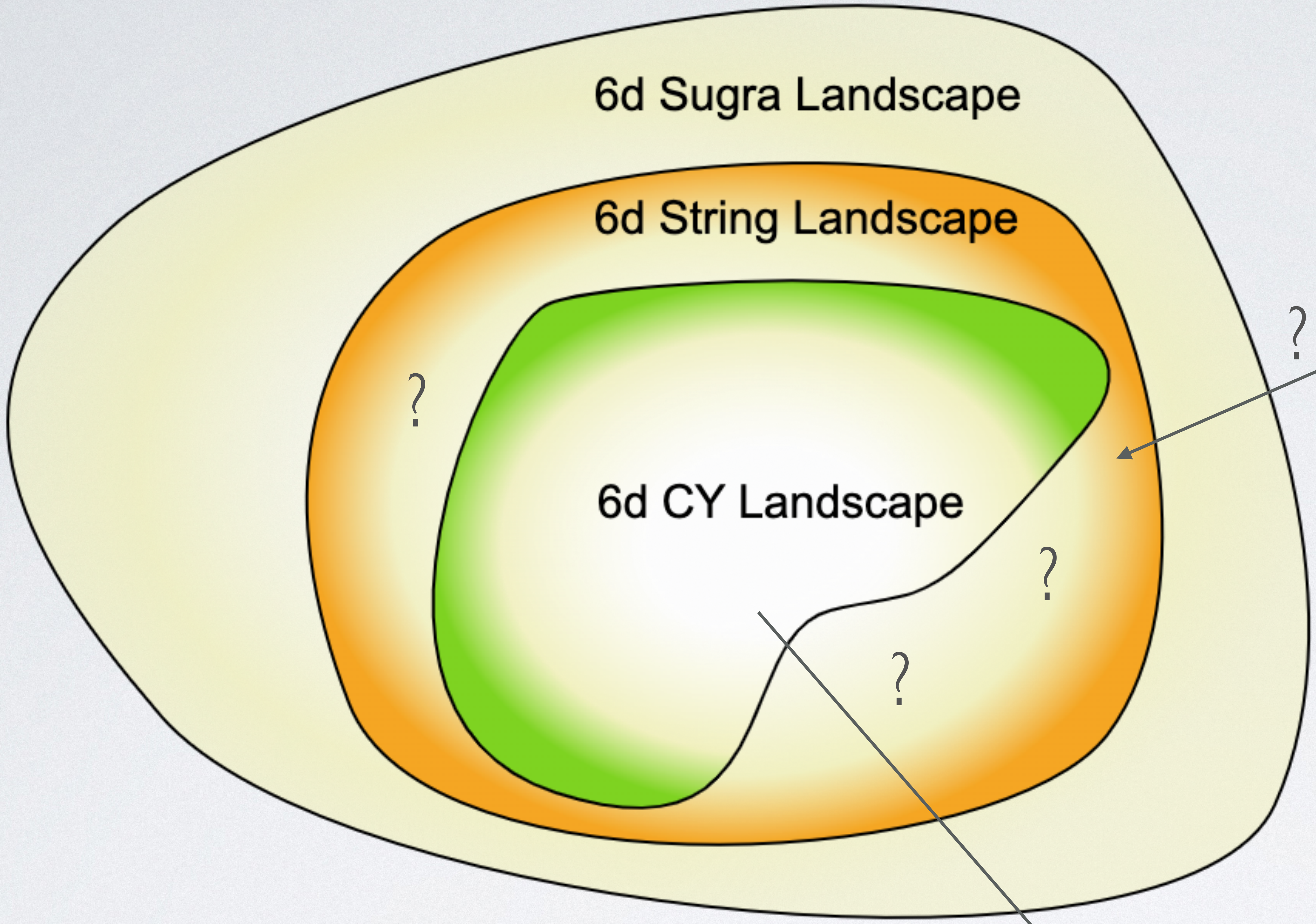

$$R^4: \quad H_{neutral} + H_{charged} - V = 273 - 29T$$

Anomalies permit: $H_{neutral} = 0$

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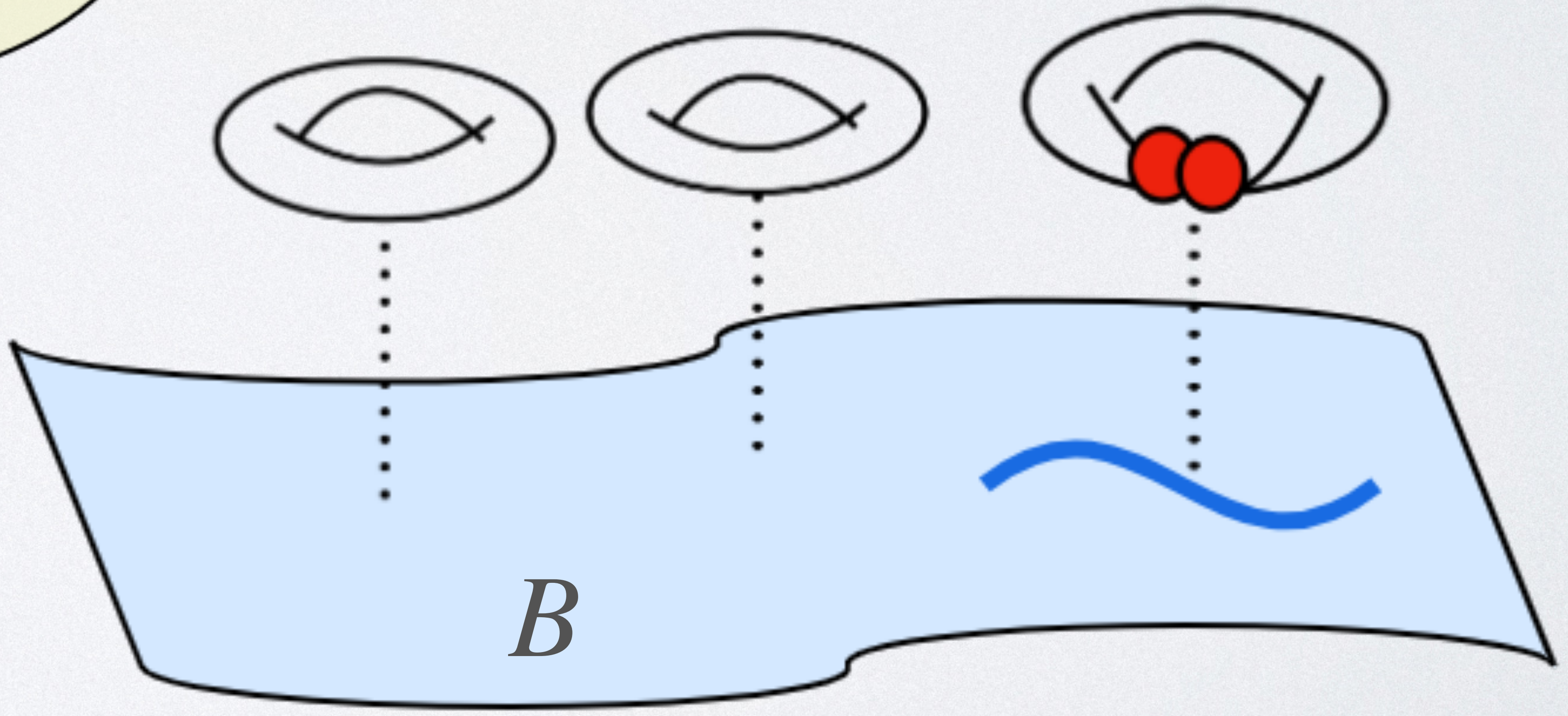

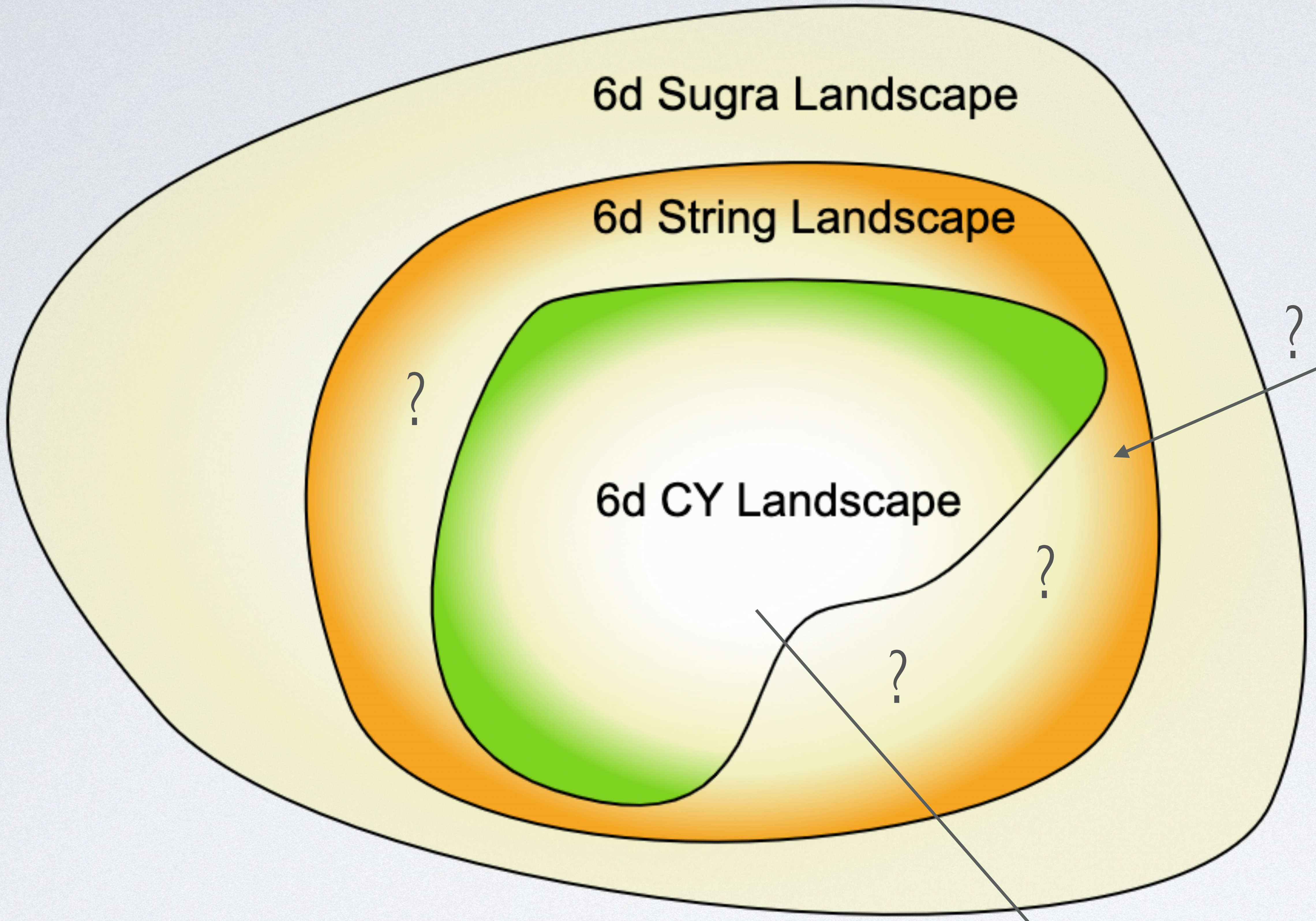

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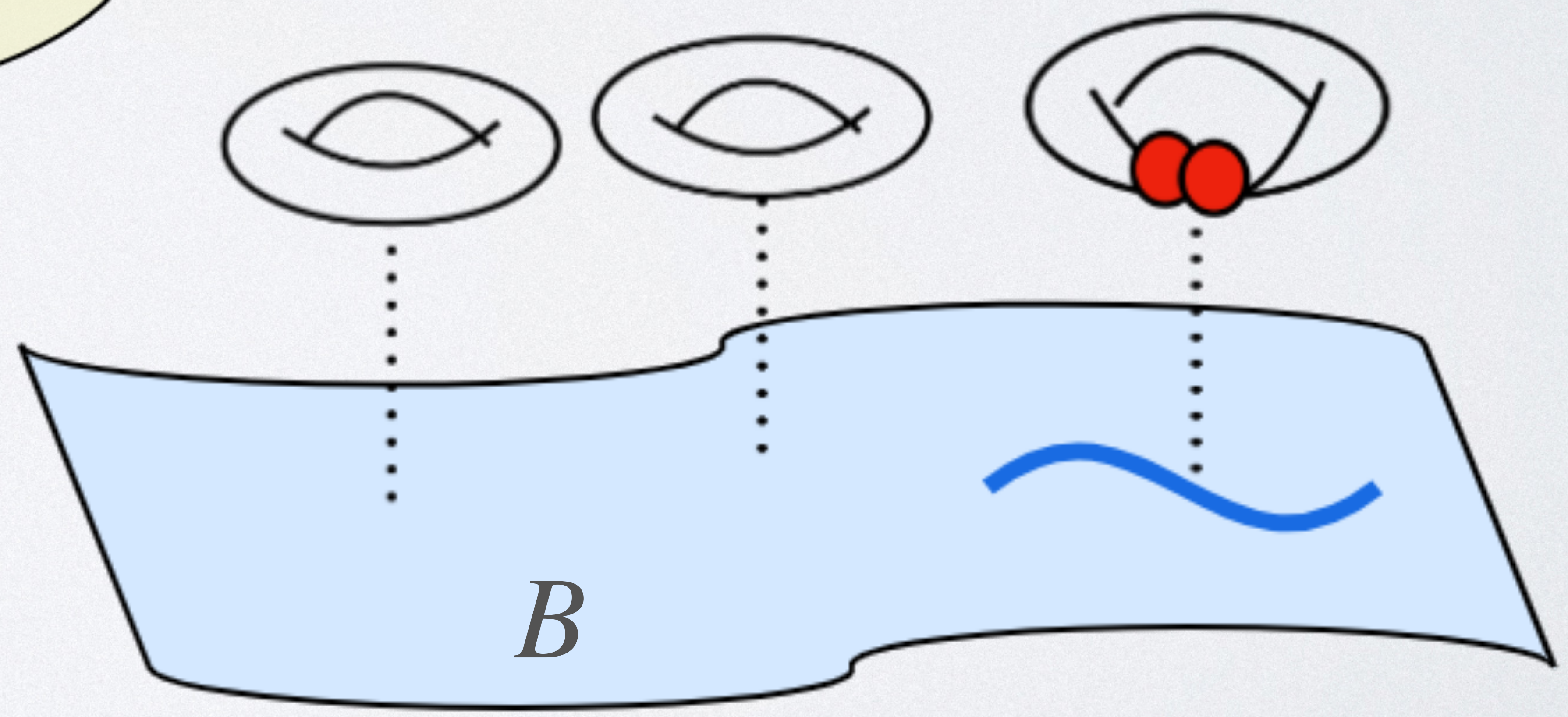

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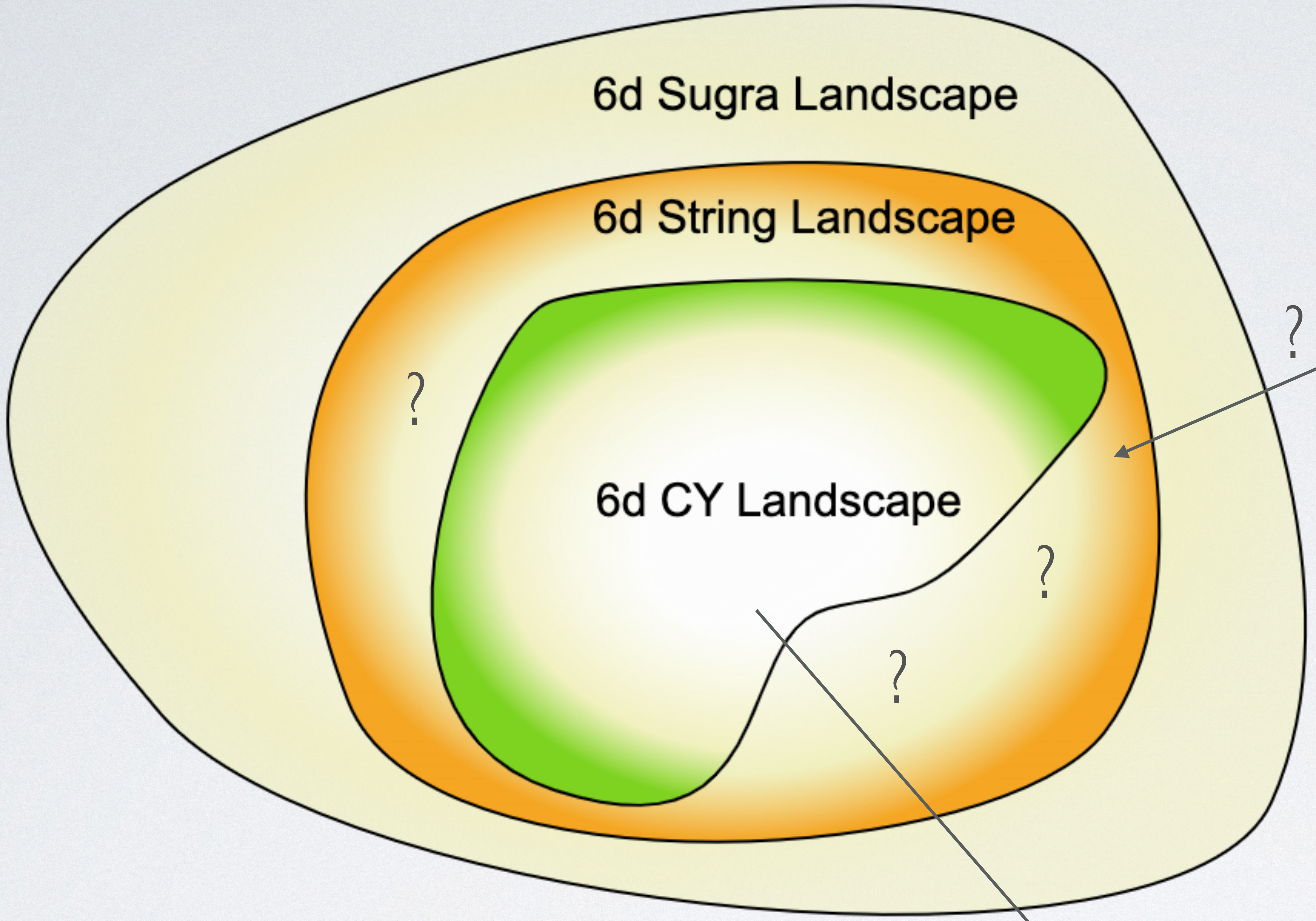

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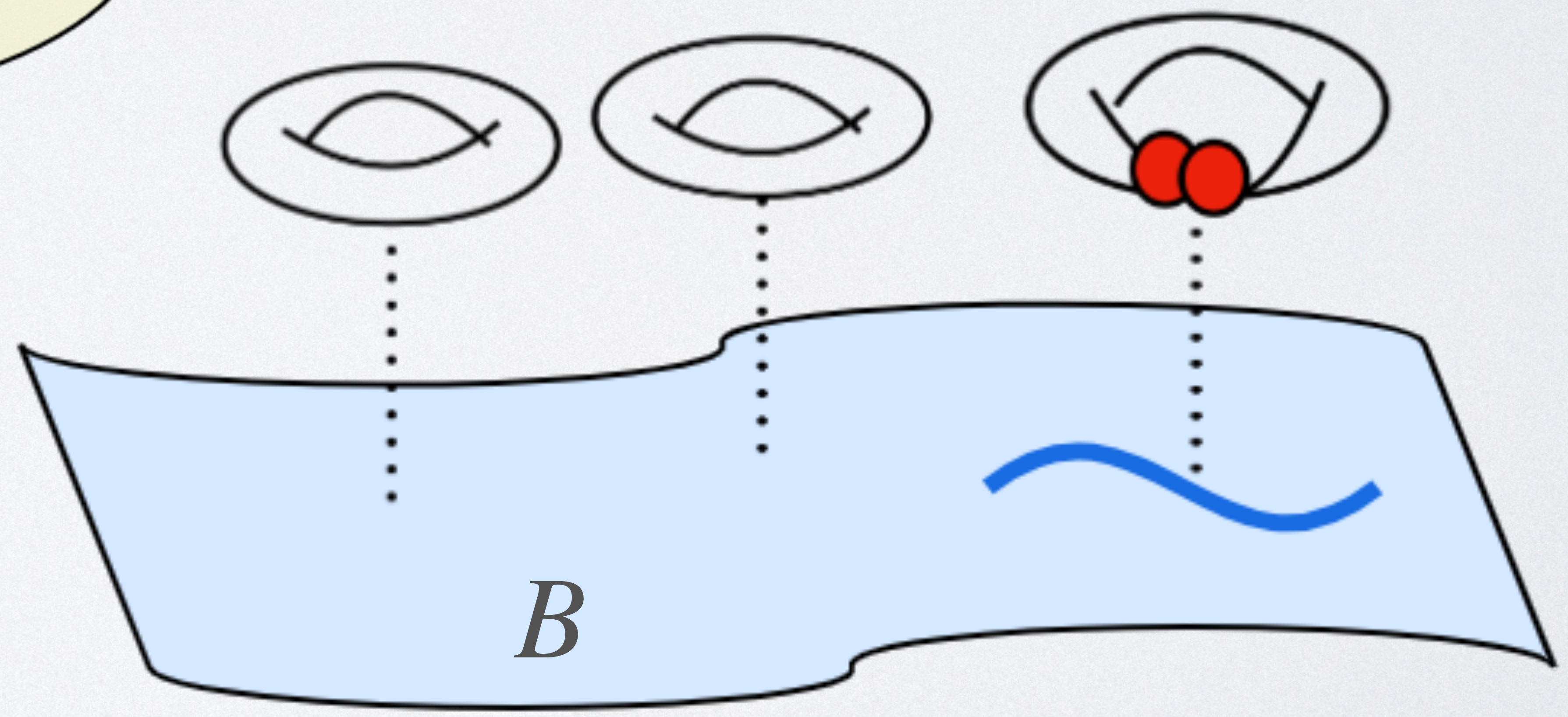
Can it become charged?



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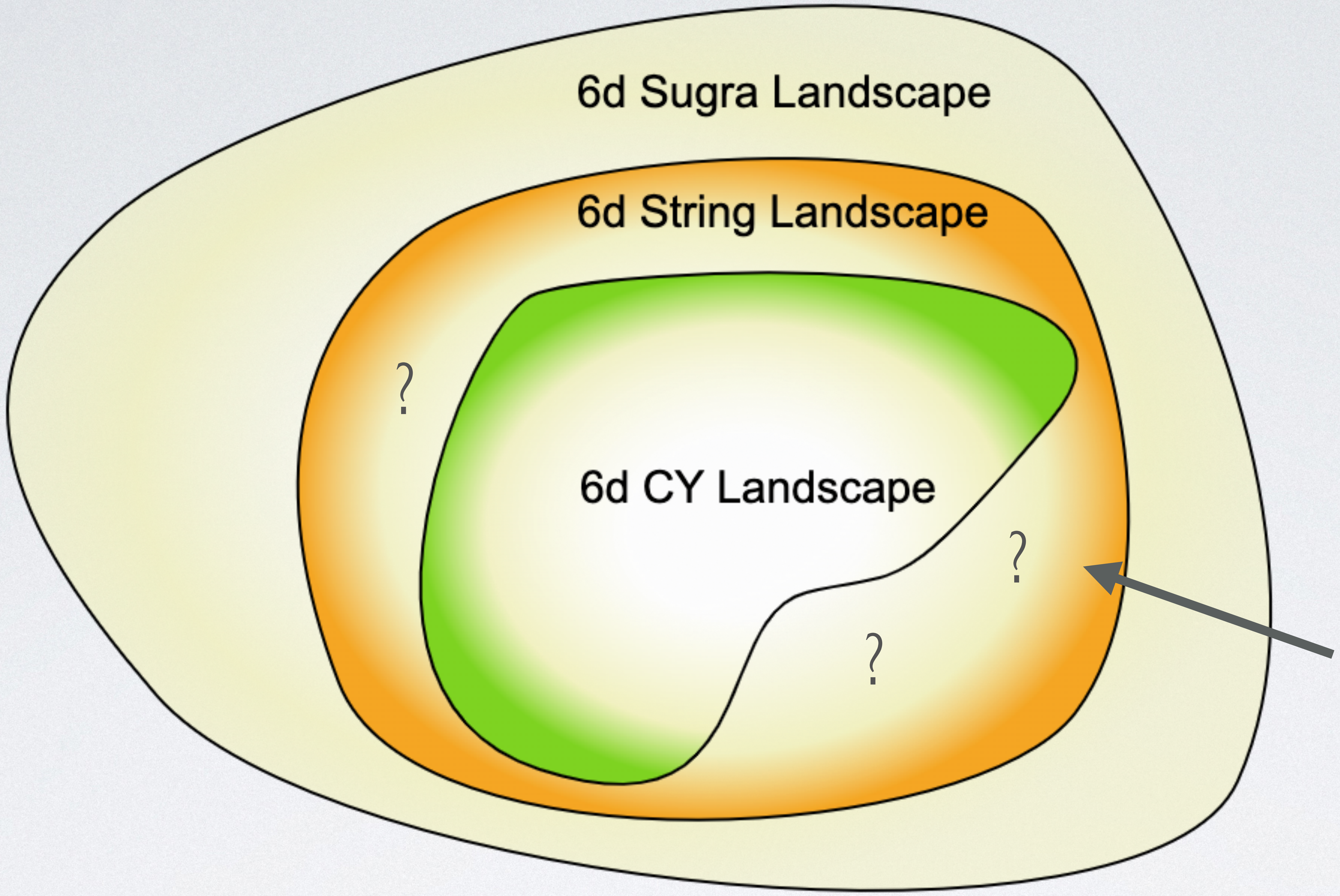
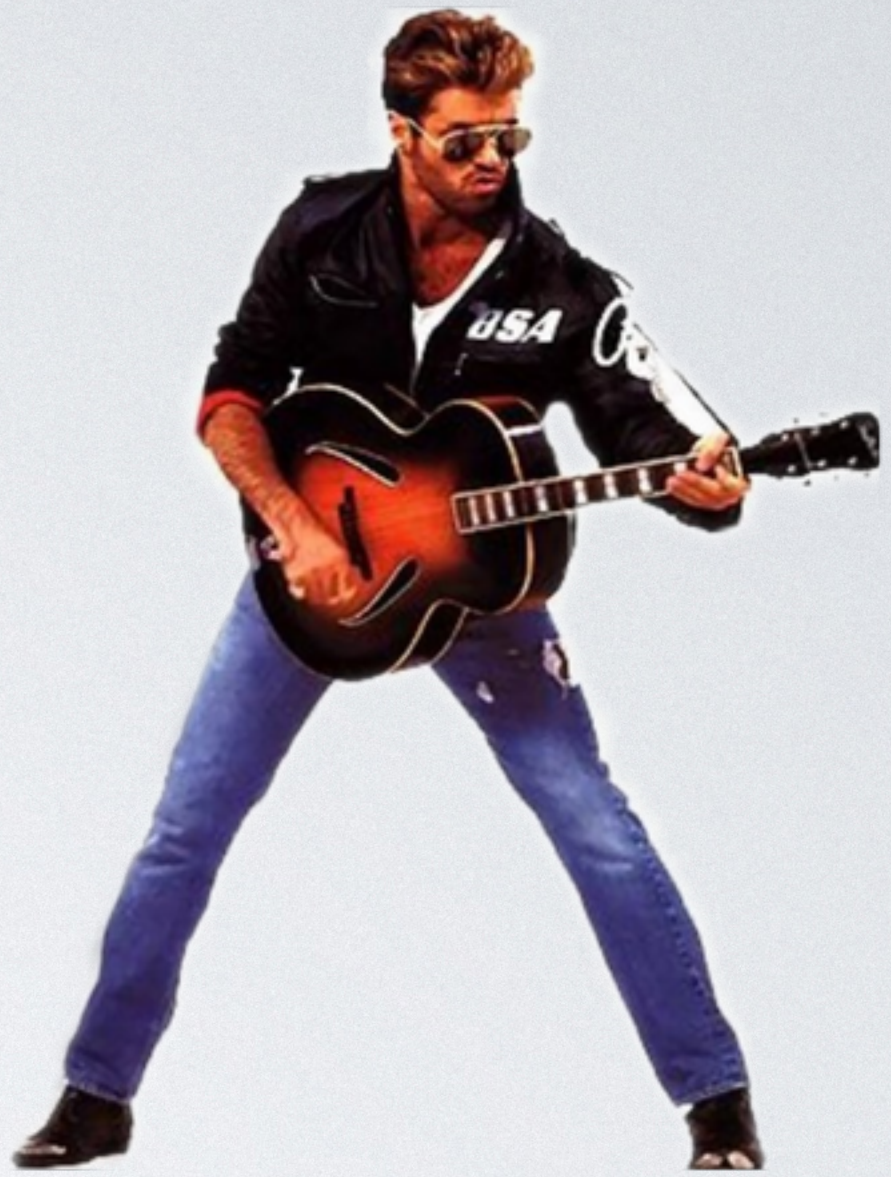
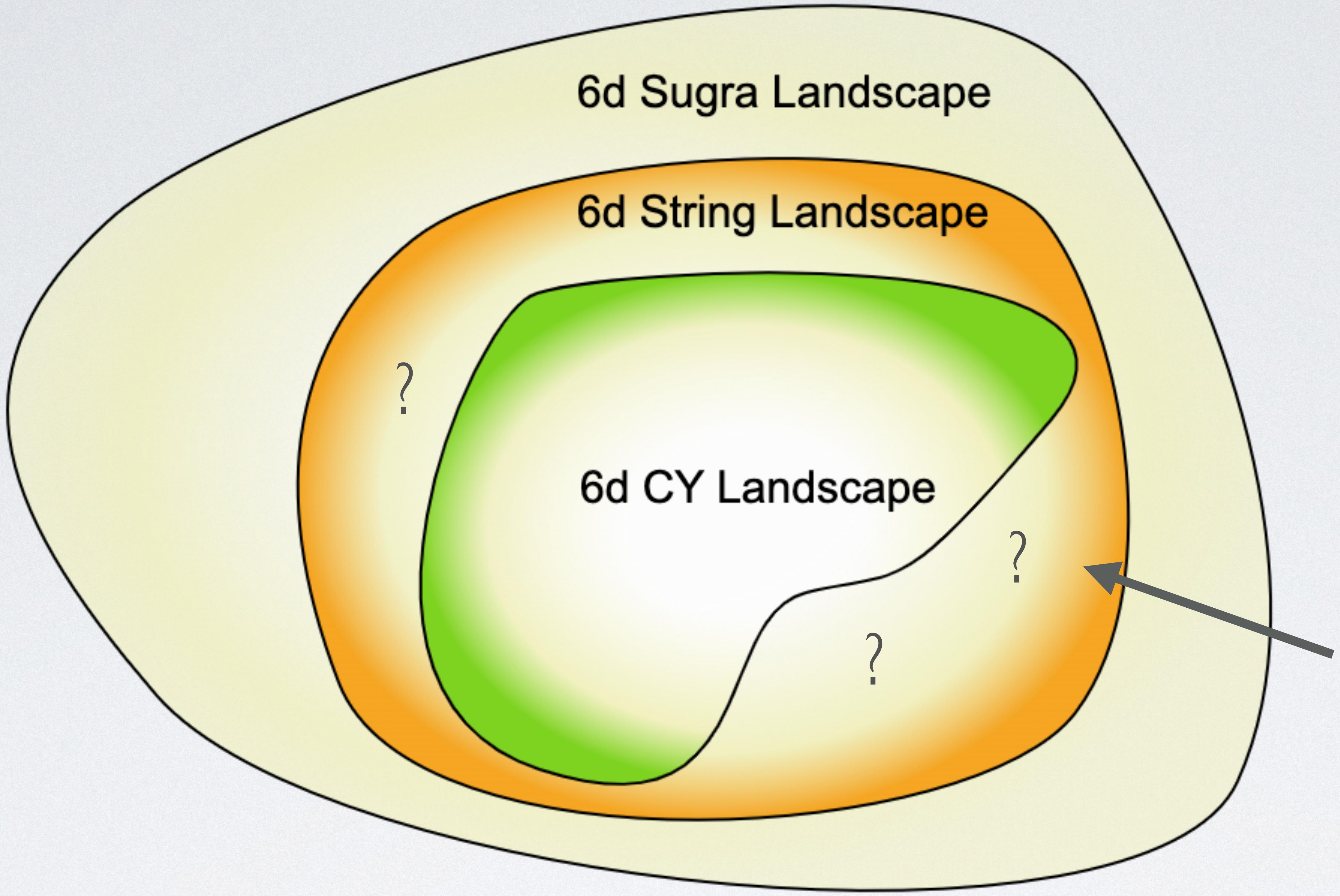
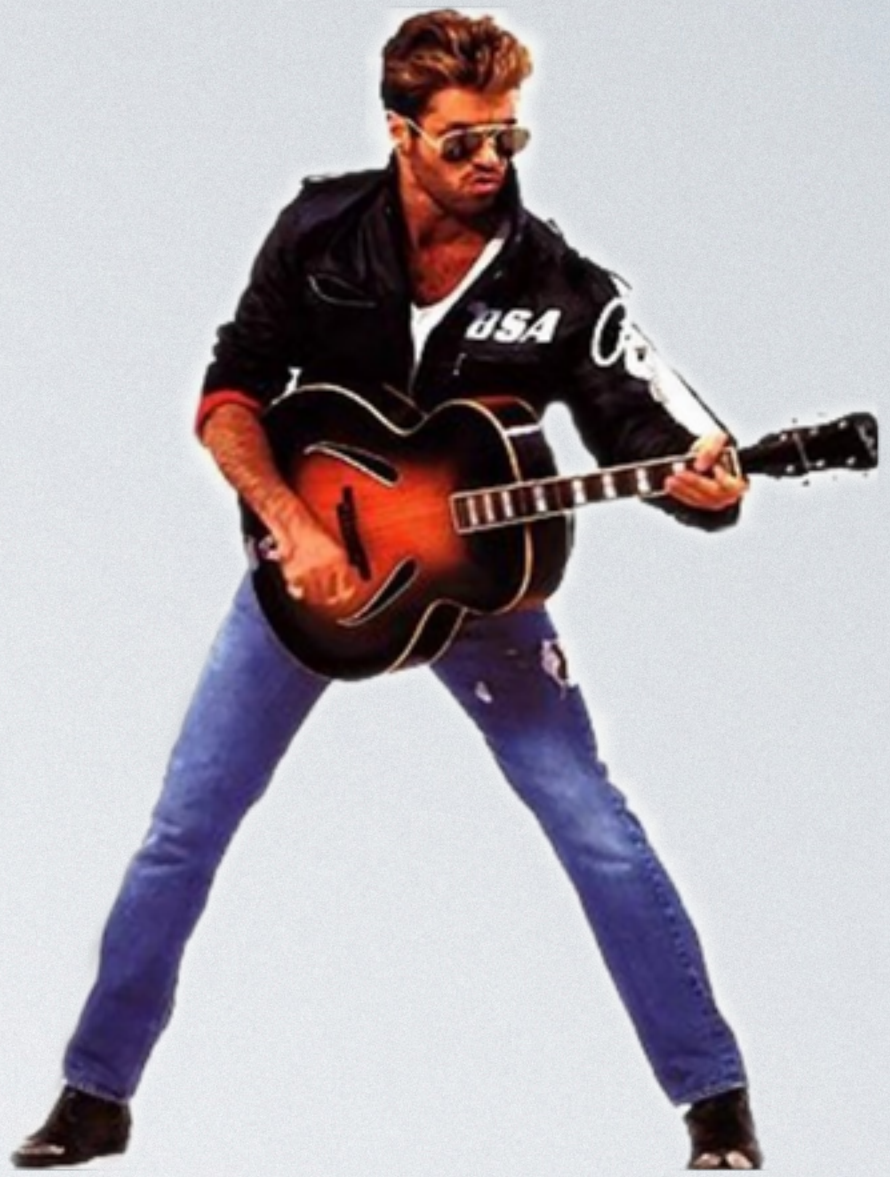




“A different corner”



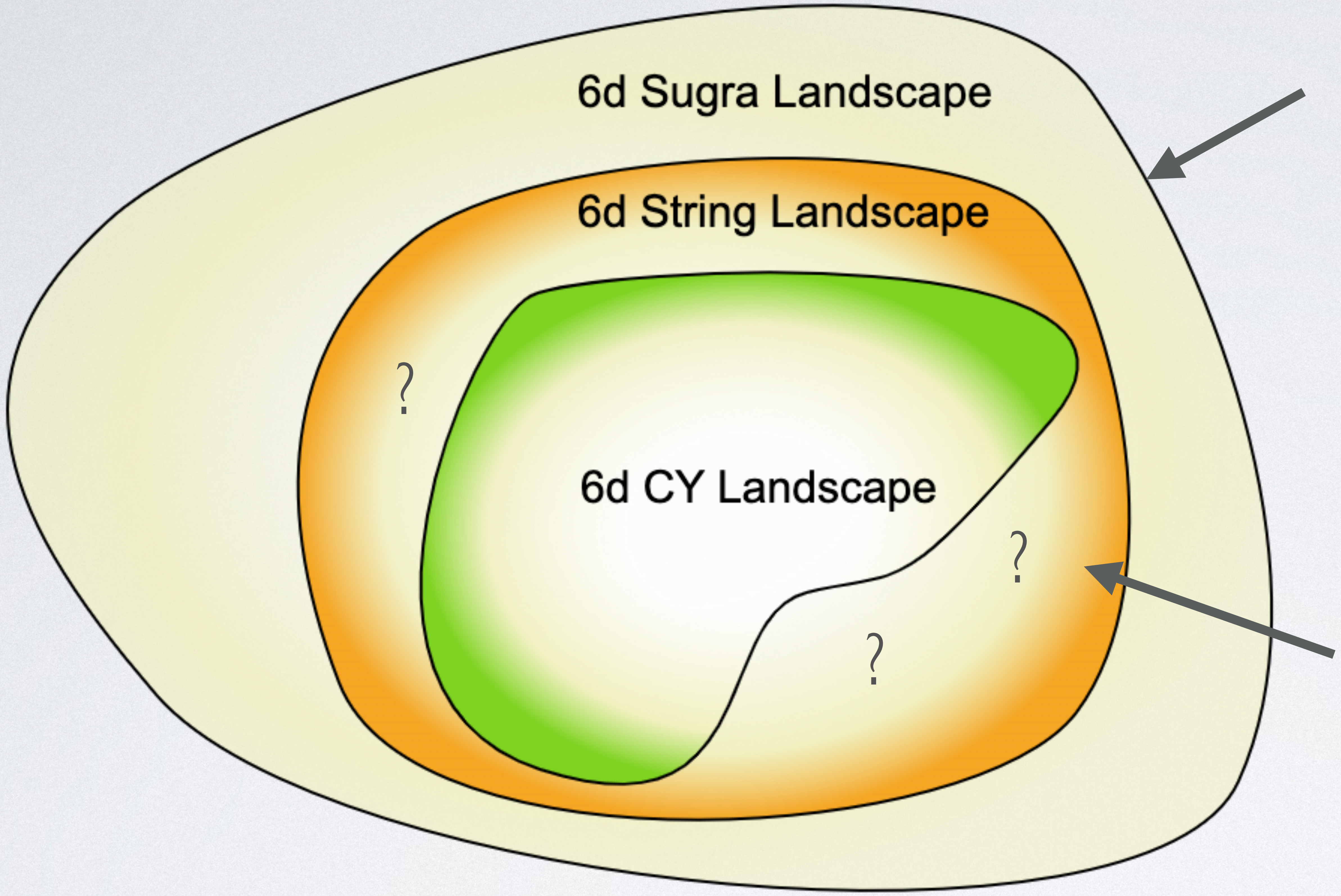


"A different corner"

Non-geometric models

Asymmetric Orbifolds

$$H_{neutral} = 0$$



Sugra Questions

- Find universal consistency conditions

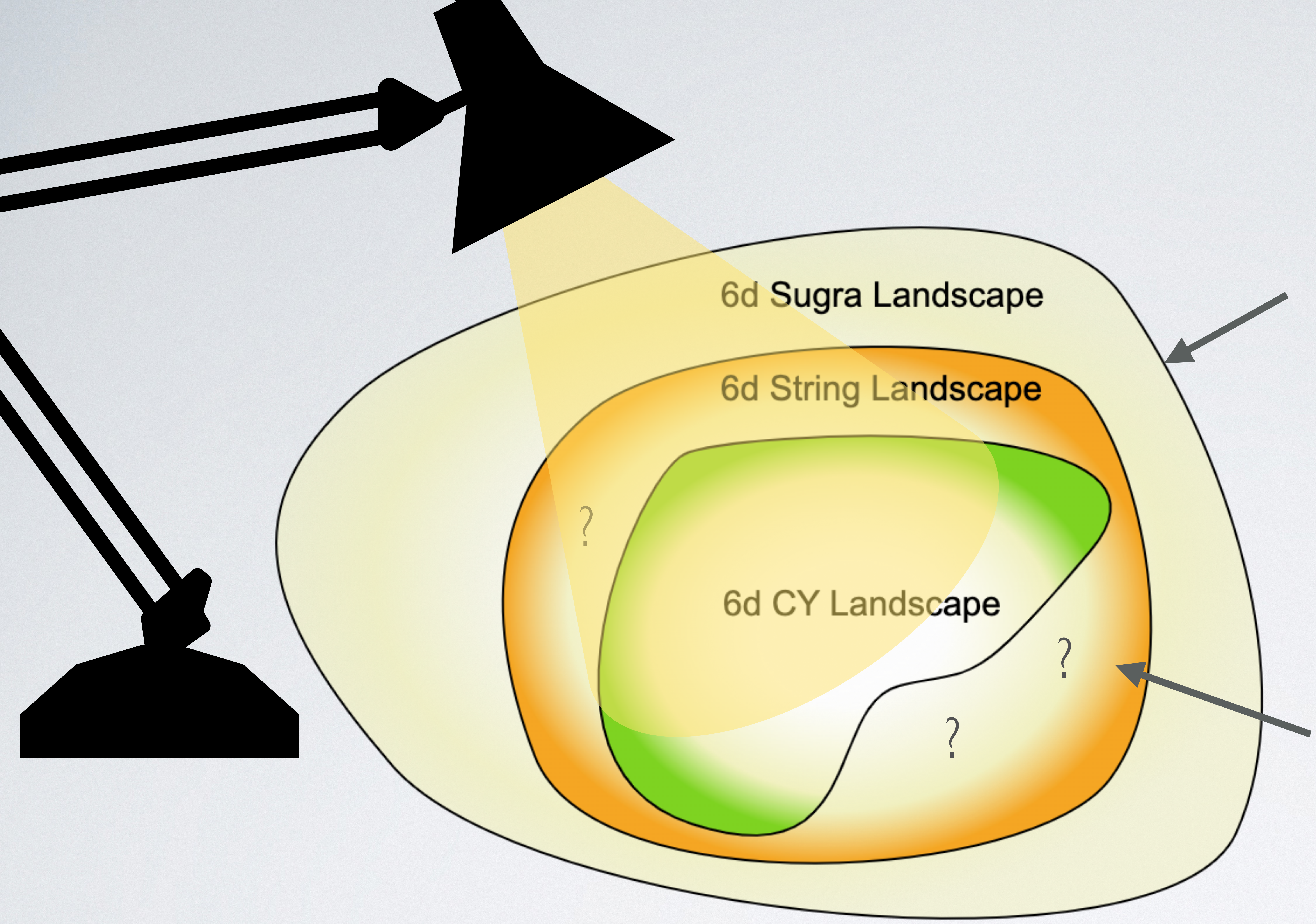
Is the Kodaira condition a Sugra condition ?

$$12\, J \cdot a \geq \sum_i \nu_i\, J \cdot b_i$$

Non-geometric models

Asymmetric Orbifolds

Connection to geometry ?



Sugra Questions

- Find universal consistency conditions

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Non-geometric models

Asymmetric Orbifolds

Connection to geometry ?

Abelian Orbifolds

- Choose the starting point: IIA, IIB, Heterotic

- Choose even self-dual lattice: $\Gamma^{D,D}(\mathfrak{g}) = \{(p_L, p_R)\,|\,p_L \in \Lambda_W(\mathfrak{g}), p_R \in \Lambda_W(\mathfrak{g}), p_L - p_R \in \Lambda_R(\mathfrak{g})\}$

$$\Gamma^{D,D}(\mathfrak{g}) + \Gamma^{16,0}(E_8 \times E_8)$$

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Lattice Automorphisms/crystallographic symmetries on T^D

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- Choose the shift: (v_L, v_R)

$$\left.\begin{matrix} [g_L, g_R] = [\exp(2\pi i \phi_L), \exp(2\pi i \phi_R)] \\ (v_L, v_R) \end{matrix}\right\} \quad |p_L, p_R> \to e^{2\pi i (p_L \cdot v_L - p_R \cdot v_R)} |g_L \cdot p_L, g_R \cdot p_R>$$

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$R = L$

Symmetric Orbifolds

$R \neq L$

Asymmetric Orbifolds

[Dixon, Harvey, Vafa, Witten 85'/86']

[Narain, Sarmadi, Vafa 87']

Abelian Orbifolds

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$R = L$

Symmetric Orbifolds

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Asymmetric Orbifolds

Type II Asymmetric Orbifold

6d $$\Gamma^{4,4}(D_4) = \{(p_L, p_R)\,|\,p_L \in \Lambda_W(D_4), p_R \in \Lambda_W(D_4), p_L - p_R \in \Lambda_R(D_4)\}$$

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Break all right moving SUSY $\phi_R = (-1)^{F_R}$

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Spectrum

T	V	$H_{charged}$	$H_{neutral}$
9	$U(1)^{12}$	$(\underline{\pm 1,0,0,0},0^8) + (\pm, \pm, \pm, \pm, 0^8)\frac{1}{2} + (\underline{\pm, \mp, \mp, \mp}, 0^8)\frac{1}{2} + (\underline{-,-,+,+}, 0^8)\frac{1}{2}$	0

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Spectrum

g_s → T

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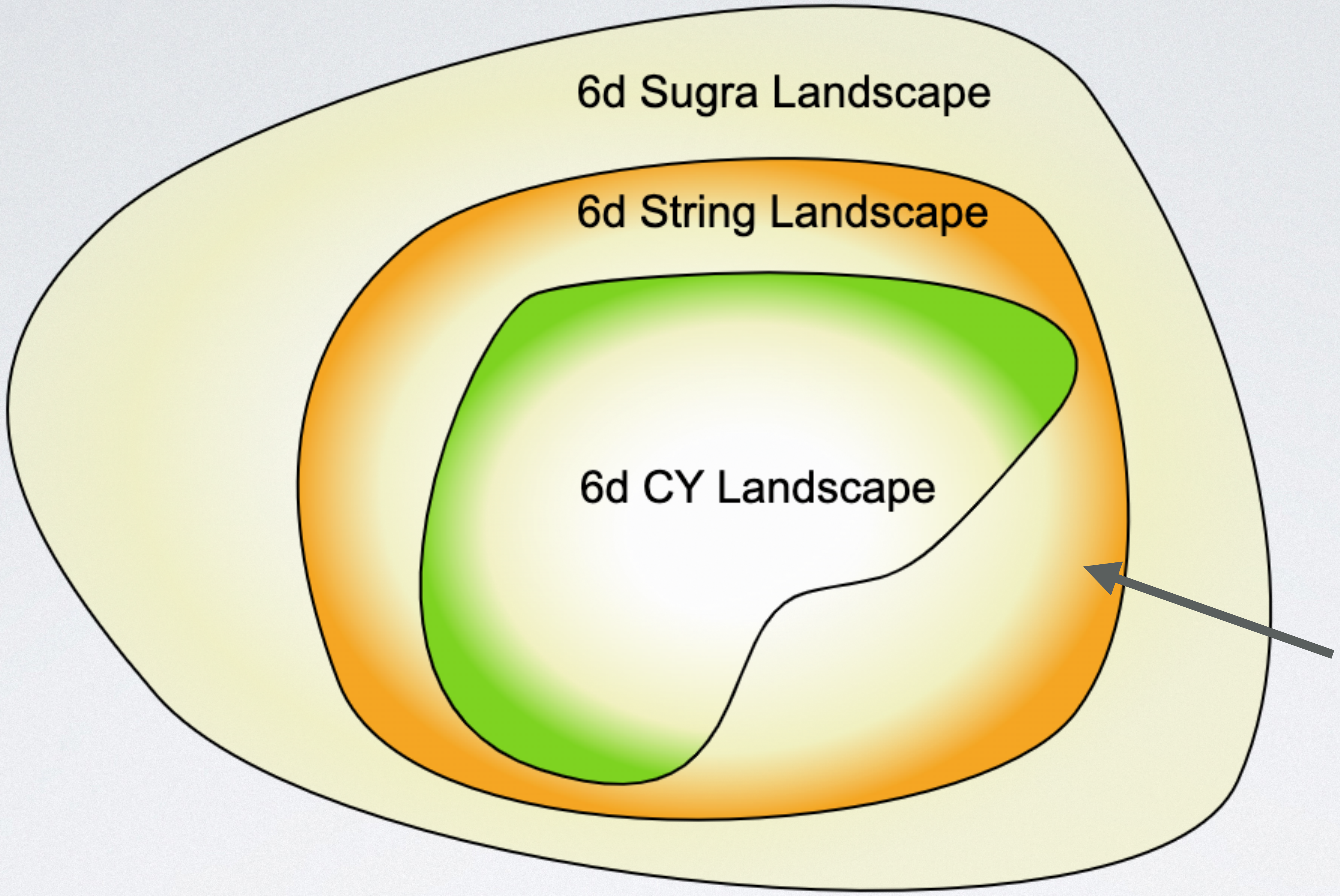
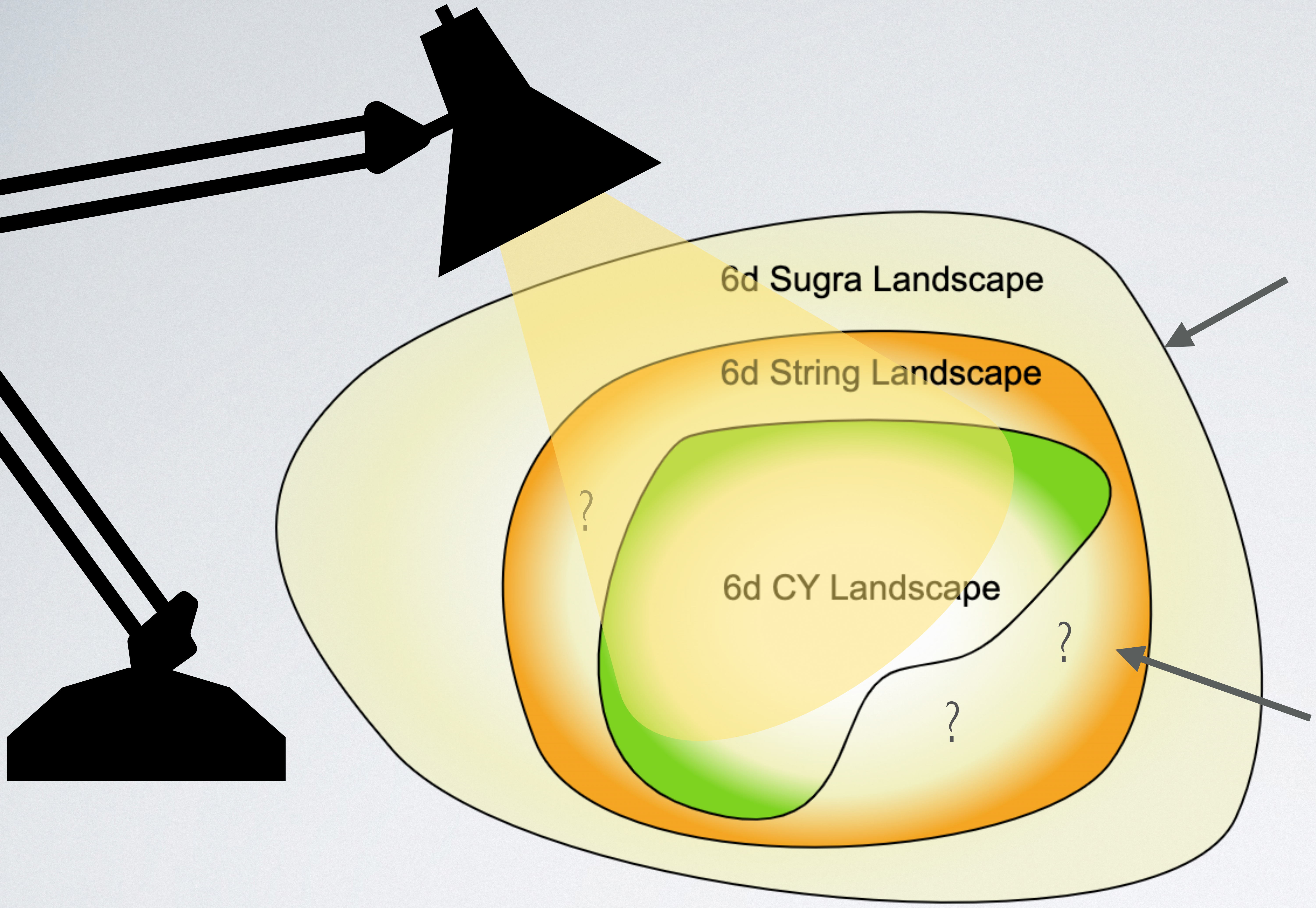


Non-geometric models

Asymmetric Orbifolds

✓ $H_{neutral} = 0$



Swampland Questions

- Find universal consistency conditions

Is the Kodaira condition a Sugra condition ?
Or
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$$12\; J \cdot a \geq \sum_i \nu_i \; J \cdot b_i$$

Non-geometric models

Asymmetric Orbifolds

Connection to geometry ?

Heterotic Asymmetric Orbifold

6d

$$\Gamma^{4,4}(A_2 \oplus A_2) + 2\Gamma^{8,0}(E_8)$$

$\mathcal{N} = 1$

$$[\exp(2\pi i \phi_L), \exp(2\pi i \phi_R)]$$

Preserve 8 supercharges

Break half right moving SUSY

$$\phi_R = (\frac{2}{3}, \frac{2}{3}) \qquad \phi_L = (0,0)$$

$$V_L = \frac{1}{3}(1^6, 0^2; 0^8)$$

Heterotic Asymmetric Orbifold

6d $\Gamma^{4,4}(A_2 \oplus A_2) + 2\Gamma^{8,0}(E_8)$

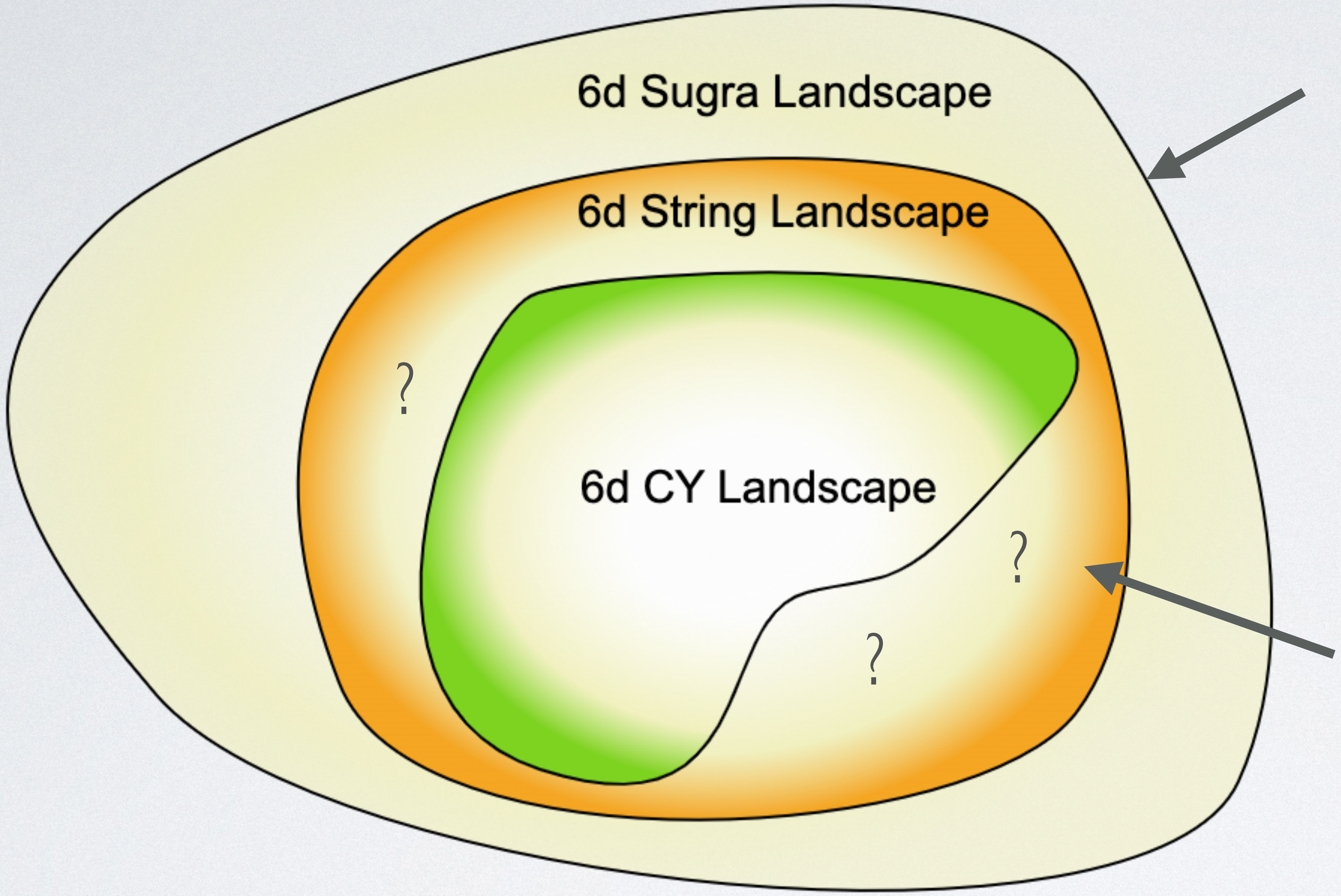
$\mathcal{N} = 1$ $[\exp(2\pi i \phi_L), \exp(2\pi i \phi_R)]$ Preserve 8 supercharges

Break half right moving SUSY $\phi_R = (\frac{2}{3}, \frac{2}{3})$ $\phi_L = (0,0)$

$$V_L = \frac{1}{3}(1^6, 0^2; 0^8)$$

Spectrum

T	V	$H_{charged}$	$H_{neutral}$
1	$E_6 \times SU(3) \times E_8 \times SU(3)^2$	$2(\mathbf{27}, \mathbf{3}, \mathbf{1}, \mathbf{1}, \mathbf{1}) + (\mathbf{27}, \mathbf{1}, \mathbf{1}, \underline{\mathbf{3}, \mathbf{1}}) + (\mathbf{27}, \mathbf{1}, \mathbf{1}, \underline{\overline{\mathbf{3}}, \mathbf{1}})$ $+(\mathbf{1}, \mathbf{3}, \mathbf{1}, \mathbf{3}, \mathbf{3}) + (\mathbf{1}, \mathbf{3}, \mathbf{1}, \underline{\mathbf{3}, \overline{\mathbf{3}}}) + (\mathbf{1}, \mathbf{3}, \mathbf{1}, \overline{\mathbf{3}}, \overline{\mathbf{3}})$	0



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Non-geometric models

Asymmetric Orbifolds

Connection to geometry ?

Heterotic Asymmetric Orbifold

Spectrum

T	V	$H_{charged}$	$H_{neutral}$
1	$E_6 \times SU(3) \times E_8 \times SU(3)^2$	$2(\mathbf{27},\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1}) + (\mathbf{27},\mathbf{1},\mathbf{1},\underline{\mathbf{3},\mathbf{1}}) + (\mathbf{27},\mathbf{1},\mathbf{1},\underline{\overline{\mathbf{3}},\mathbf{1}})$ $+(\mathbf{1},\mathbf{3},\mathbf{1},\mathbf{3},\mathbf{3}) + (\mathbf{1},\mathbf{3},\mathbf{1},\underline{\mathbf{3},\overline{\mathbf{3}}}) + (\mathbf{1},\mathbf{3},\mathbf{1},\overline{\mathbf{3}},\overline{\mathbf{3}})$	0

Higgsing

T	V	$H_{charged}$	$H_{neutral}$
1	E_8	0	492

Heterotic Asymmetric Orbifold

Spectrum

T	V	$H_{charged}$	$H_{neutral}$
1	$E_6 \times SU(3) \times E_8 \times SU(3)^2$	$2(\mathbf{27},\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1}) + (\mathbf{27},\mathbf{1},\mathbf{1},\underline{\mathbf{3},\mathbf{1}}) + (\mathbf{27},\mathbf{1},\mathbf{1},\underline{\overline{\mathbf{3}},\mathbf{1}})$ $+(\mathbf{1},\mathbf{3},\mathbf{1},\mathbf{3},\mathbf{3}) + (\mathbf{1},\mathbf{3},\mathbf{1},\underline{\mathbf{3},\overline{\mathbf{3}}}) + (\mathbf{1},\mathbf{3},\mathbf{1},\overline{\mathbf{3}},\overline{\mathbf{3}})$	0

Higgsing

T	V	$H_{charged}$	$H_{neutral}$
1	E_8	0	492

Familiar?

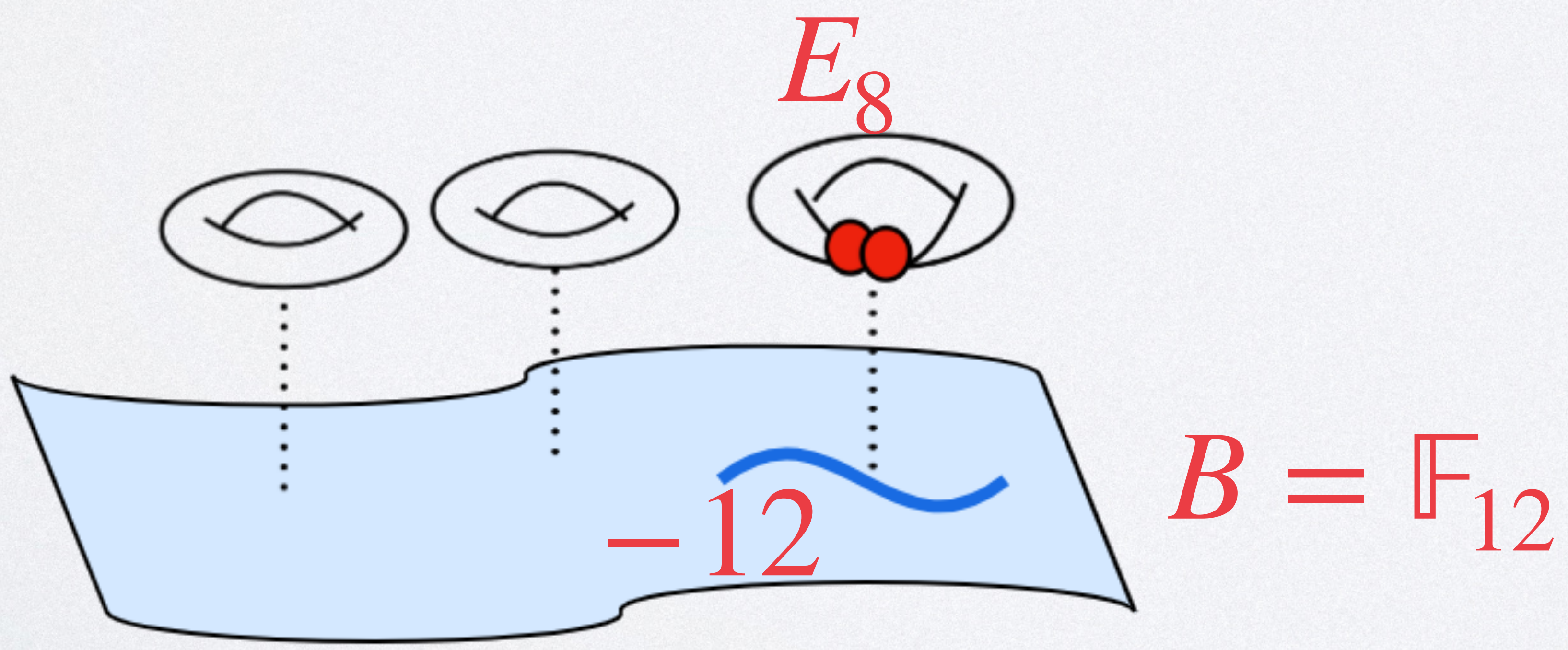
Heterotic Asymmetric Orbifold

Spectrum

T	V	$H_{charged}$	$H_{neutral}$
1	$E_6 \times SU(3) \times E_8 \times SU(3)^2$	$2(\mathbf{27},\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1}) + (\mathbf{27},\mathbf{1},\mathbf{1},\underline{\mathbf{3},\mathbf{1}}) + (\mathbf{27},\mathbf{1},\mathbf{1},\underline{\overline{\mathbf{3}},\mathbf{1}})$ $+(\mathbf{1},\mathbf{3},\mathbf{1},\mathbf{3},\mathbf{3}) + (\mathbf{1},\mathbf{3},\mathbf{1},\underline{\mathbf{3},\overline{\mathbf{3}}}) + (\mathbf{1},\mathbf{3},\mathbf{1},\overline{\mathbf{3}},\overline{\mathbf{3}})$	0

Higgsing

T	V	$H_{charged}$	$H_{neutral}$
1	E_8	0	492



Heterotic Asymmetric Orbifold

T	V	$H_{charged}$	$H_{neutral}$
1	$E_6 \times SU(3) \times E_8 \times SU(3)^2$	$2(\mathbf{27},\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1}) + (\mathbf{27},\mathbf{1},\mathbf{1},\underline{\mathbf{3},\mathbf{1}}) + (\mathbf{27},\mathbf{1},\mathbf{1},\underline{\overline{\mathbf{3}},\mathbf{1}})$ $+(\mathbf{1},\mathbf{3},\mathbf{1},\mathbf{3},\mathbf{3}) + (\mathbf{1},\mathbf{3},\mathbf{1},\underline{\mathbf{3},\overline{\mathbf{3}}}) + (\mathbf{1},\mathbf{3},\mathbf{1},\overline{\mathbf{3}},\overline{\mathbf{3}})$	0

$\downarrow$ Higgsing

Calabi-Yau threefold with base $\mathbb{F}_{12}$

T	V	$H_{charged}$	$H_{neutral}$
1	E_8	0	492

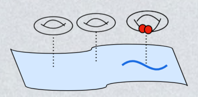
$\downarrow$ Duality

Heterotic on K3 with Instanton number (0,24)

[9505105]
Kachru, Vafa

T^2 → 4d

Transitions

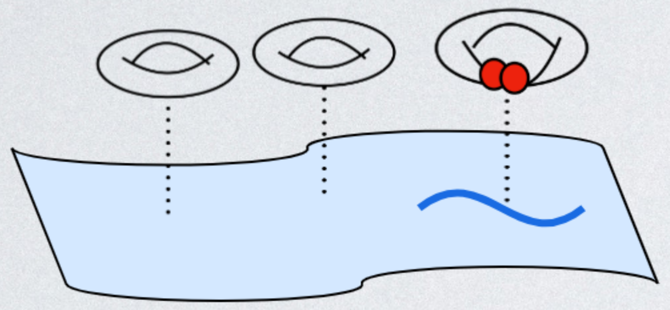


Conifold like

Heterotic Asymmetric Orbifold

$g_S \to \infty$ ↑ $Vol(B) \to 0$

↕ Higgsing/UnHiggsing



Calabi-Yau threefold with base $\mathbb{F}_{12}$

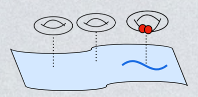
↕ Duality

Heterotic on K3 with Instanton number $(0,24)$

[9505105]
Kachru, Vafa

T^2 → 4d

Transitions

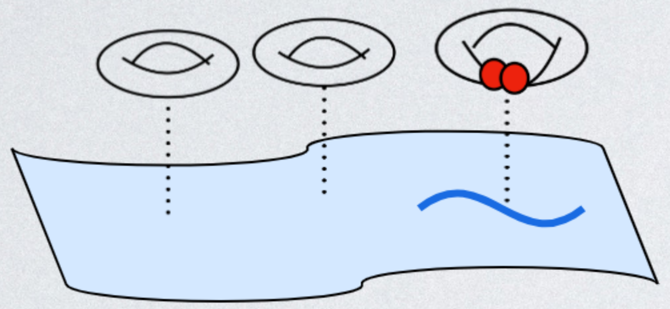


Conifold like

Heterotic Asymmetric Orbifold

$g_S \to \infty$ ↑ $Vol(B) \to 0$

↕ Higgsing/UnHiggsing



Calabi-Yau threefold with base $\mathbb{F}_{12}$

$R_{\text{self-dual}}$

g_H small

↕ Duality

Heterotic on K3 with Instanton number $(0,24)$

$\Gamma^{4,4}(D_4)$

$\phi_R = (-1)^{F_R}$ $\phi_L = (\frac{1}{2}, \frac{1}{2})$

Type II AO

$\Gamma^{4,4}(A_2 \oplus A_2) + 2\Gamma^{8,0}(E_8)$

$\phi_R = (\frac{2}{3}, \frac{2}{3})$ $\phi_L = (0,0)$

$$V_L = \frac{1}{3}(1^6, 0^2; 0^8)$$

Heterotic AO1

$\Gamma^{4,4}(D_4) + 2\Gamma^{8,0}(E_8)$

$\phi_R = (\frac{1}{2}, \frac{1}{2})$ $\phi_L = (0,0)$

$$V_L = \frac{1}{2}(1^2, 0^6; 1^2, 0^6)$$

Heterotic AO2

$\Gamma^{4,4}(D_4) + 2\Gamma^{8,0}(E_8)$

$\phi_R = (\frac{1}{2}, \frac{1}{2})$ $\phi_L = (0,0)$

$$E_8 \leftrightarrow E_8$$

Heterotic AO3

$\Gamma^{4,4}(D_4)$

$\phi_R = (-1)^{F_R}$ $\quad \phi_L = (\frac{1}{2}, \frac{1}{2})$

Type II AO

$U(1)^{12} + H_c$

$\Gamma^{4,4}(A_2 \oplus A_2) + 2\Gamma^{8,0}(E_8)$

$\phi_R = (\frac{2}{3}, \frac{2}{3})$ $\quad \phi_L = (0,0)$

$$V_L = \frac{1}{3}(1^6, 0^2; 0^8)$$

Heterotic AO1

$E_6 \times SU(3) \times E_8 \times SU(3)^2 + H_c$

$\Gamma^{4,4}(D_4) + 2\Gamma^{8,0}(E_8)$

$\phi_R = (\frac{1}{2}, \frac{1}{2})$ $\quad \phi_L = (0,0)$

$$V_L = \frac{1}{2}(1^2, 0^6; 1^2, 0^6)$$

Heterotic AO2

$E_7 \times SU(2) \times E_7 \times SU(2) \times SO(8) + H_c$

$\Gamma^{4,4}(D_4) + 2\Gamma^{8,0}(E_8)$

$\phi_R = (\frac{1}{2}, \frac{1}{2})$ $\quad \phi_L = (0,0)$

$$E_8 \leftrightarrow E_8$$

Heterotic AO3

$E_8 \times SO(8) + H_c$

Kodaira condition ✗

$\Gamma^{4,4}(D_4)$

$\phi_R = (-1)^{F_R}$ $\phi_L = (\frac{1}{2}, \frac{1}{2})$

Type II AO

$U(1)^{12} + H_c$

Calabi-Yau dP_9

Heterotic
K3+ NS5 branes

$\Gamma^{4,4}(A_2 \oplus A_2) + 2\Gamma^{8,0}(E_8)$

$\phi_R = (\frac{2}{3}, \frac{2}{3})$ $\phi_L = (0,0)$

$$V_L = \frac{1}{3}(1^6, 0^2; 0^8)$$

Heterotic AO1

$E_6 \times SU(3) \times E_8 \times SU(3)^2 + H_c$

Calabi-Yau $\mathbb{F}_{12}$

Heterotic
K3 $(0,24)$

$\Gamma^{4,4}(D_4) + 2\Gamma^{8,0}(E_8)$

$\phi_R = (\frac{1}{2}, \frac{1}{2})$ $\phi_L = (0,0)$

$$V_L = \frac{1}{2}(1^2, 0^6; 1^2, 0^6)$$

Heterotic AO2

$E_7 \times SU(2) \times E_7 \times SU(2) \times SO(8) + H_c$

Calabi-Yau $\mathbb{F}_0$

Heterotic
K3 $(12,12)$

$\Gamma^{4,4}(D_4) + 2\Gamma^{8,0}(E_8)$

$\phi_R = (\frac{1}{2}, \frac{1}{2})$ $\phi_L = (0,0)$

$$E_8 \leftrightarrow E_8$$

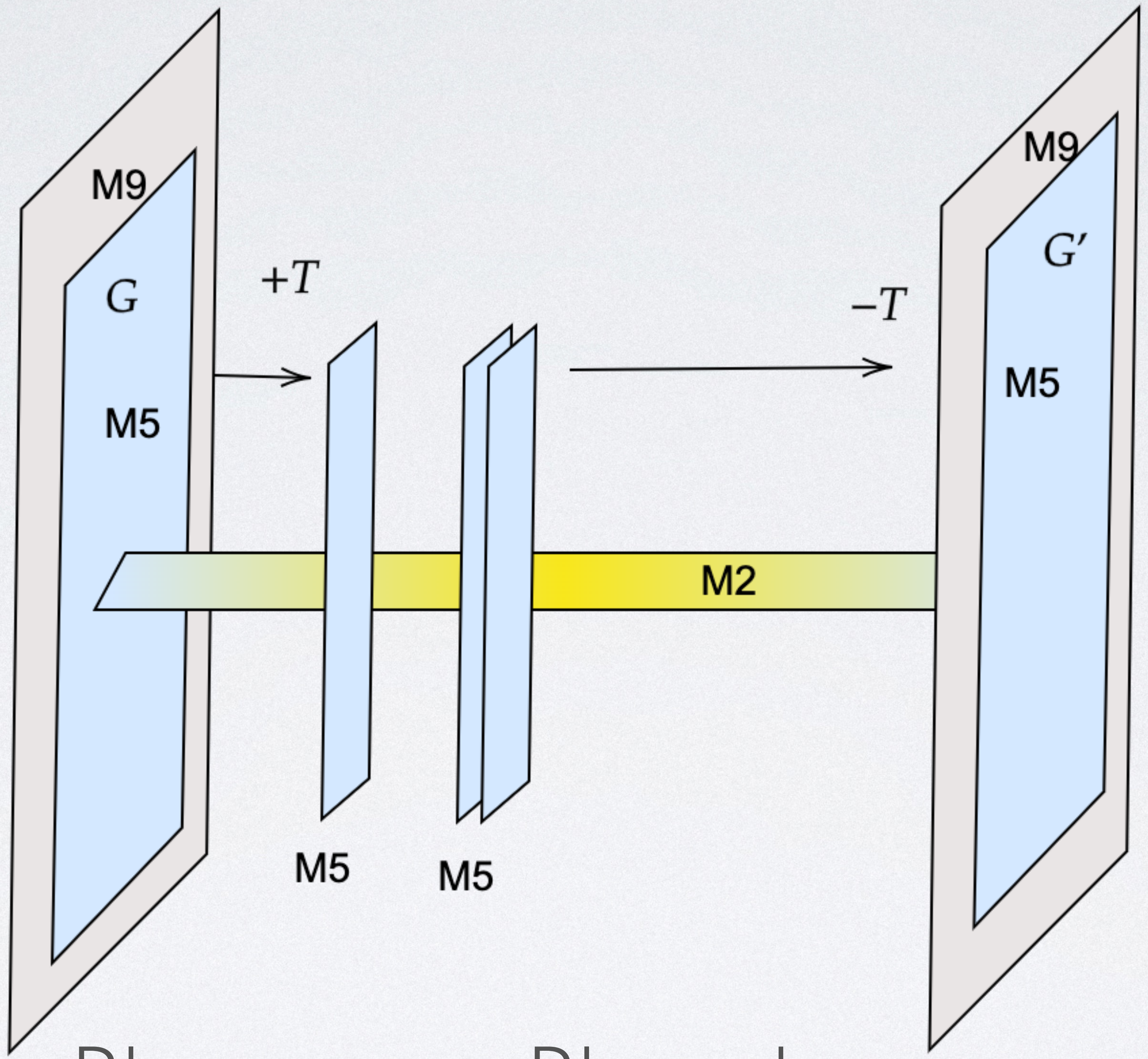
Heterotic AO3

$E_8 \times SO(8) + H_c$

Calabi-Yau $\mathbb{F}_3$

Heterotic
K3 $(9,15)$

M-theory on $K3 \times S^1/\mathbb{Z}_2$
Transitions



Blow up Blow down

F-theory

Type II AO
$U(1)^{12} + H_c$
Calabi-Yau dP_9
Heterotic
K3+ NS5 branes
Heterotic AO1
$E_6 \times SU(3) \times E_8 \times SU(3)^2 + H_c$
Calabi-Yau $\mathbb{F}_{12}$
Heterotic
K3 (0,24)
Heterotic AO2
$E_7 \times SU(2) \times E_7 \times SU(2) \times SO(8) + H_c$
Calabi-Yau $\mathbb{F}_0$
Heterotic
K3 (12,12)
Heterotic AO3
$E_8 \times SO(8) + H_c$
Calabi-Yau $\mathbb{F}_0$
Heterotic
K3 (9,15)

Consider theories on S^1 with Wilson lines

6d

Type II AO

$U(1)^{12} + H_c$

$T = 9$

Heterotic AO1

$E_6 \times SU(3) \times E_8 \times SU(3)^2 + H_c$

$T = 1$

Heterotic AO2

$E_7 \times SU(2) \times E_7 \times SU(2) \times SO(8) + H_c$

$T = 1$

Heterotic AO3

$E_8 \times SO(8) + H_c$

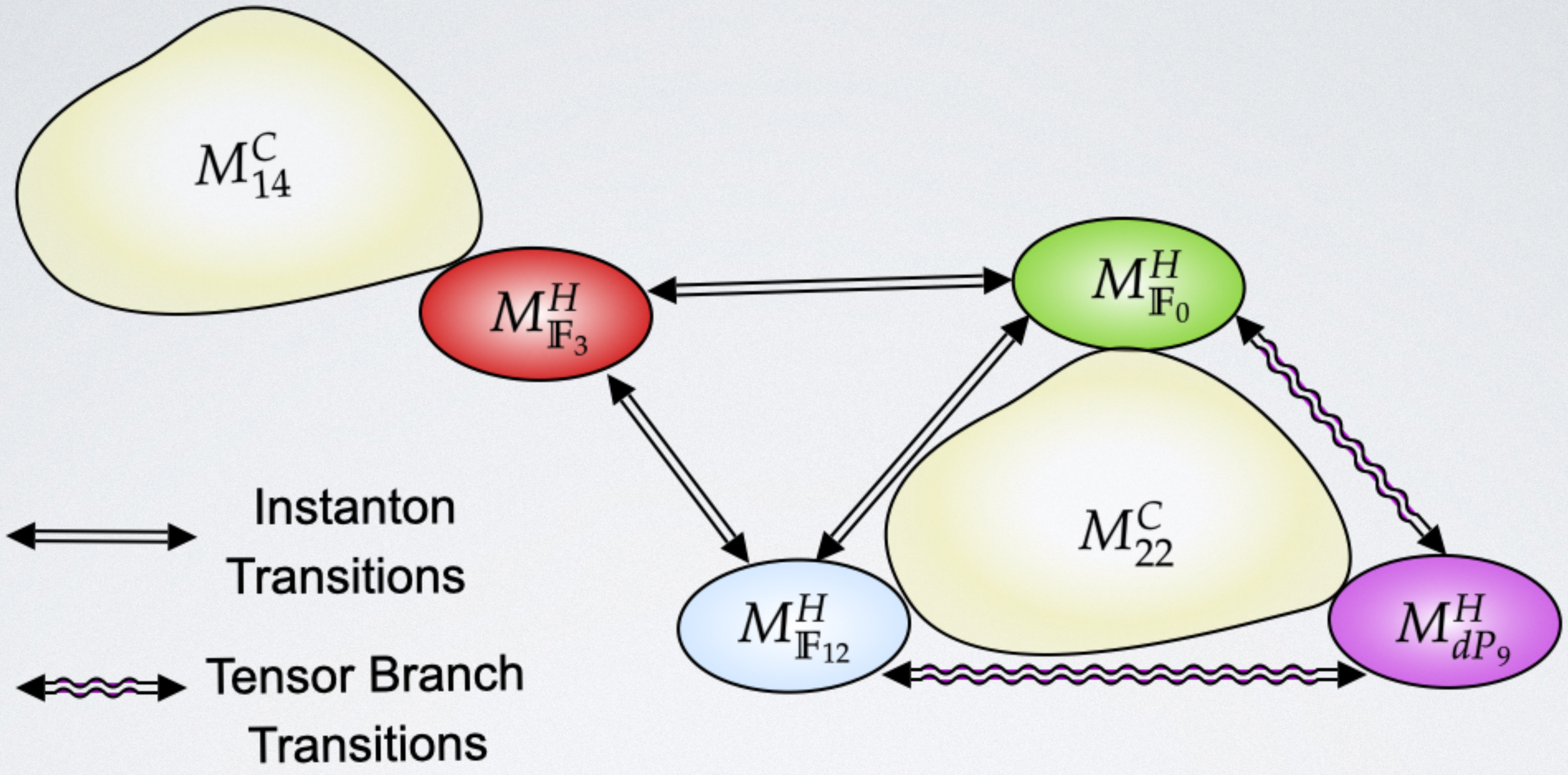
$T = 1$

5d on Coulomb branch

$U(1)^{22}$

$U(1)^{14}$

Connectedness of String Vacua



M^C Coulomb Branch

M^H Higgs Branch

More 5d models with no hypers ?

Freely Acting Orbifolds

Type II AO

$$\Gamma^{5,5} = \Gamma^{4,4} + \Gamma^{1,1}$$

$\uparrow$ $\mathbb{Z}_N$ twist $\quad$ $\uparrow$ Shift

Heterotic AO

$$\Gamma^{21,5} = \Gamma^{20,4} + \Gamma^{1,1}$$

$\uparrow$ $\mathbb{Z}_N$ twist $\quad$ $\uparrow$ Shift

Twisted sectors become massive

Similar examples

[Gkoumtoumis, Hull, Stemerdink, Vandoren 23']

More 5d models with no hypers ?

rank	type	lattice $+\Gamma^{1,1}$	twist	order
2	II	$\Gamma^{4,4}(D_4)$	$\phi_L = (\frac{1}{6}, \frac{3}{6})$ $\phi_R = (\frac{1}{4}, \frac{1}{4})$	12
4	II	$\Gamma^{4,4}(D_4)$	$\phi_L = (0, \frac{2}{3})$ $\phi_R = (\frac{1}{4}, \frac{1}{4})$	12
6	II	$\Gamma^{4,4}(A_2 \times A_2)$	$\phi_L = (1, 0)$ $\phi_R = (\frac{1}{3}, \frac{1}{3})$	6
8	II	$\Gamma^{4,4}(D_4)$	$\phi_L = (\frac{1}{2}, 0)$ $\phi_R = (\frac{1}{4}, \frac{1}{4})$	4
12	Het	$2\Gamma^{2,2}(A_2) + 2\Gamma^{8,0}(E_8)$	$\phi_R = (\frac{1}{6}, \frac{1}{6})$ $\Gamma^{2,2}(A_2) \leftrightarrow \Gamma^{2,2}(A_2)$ $\Gamma^{8,0}(E_8) \leftrightarrow \Gamma^{8,0}(E_8)$ $V_L = (0^8; 0^8)$	12
14	Het	$\Gamma^{4,4}(D_4) + 2\Gamma^{8,0}(E_8)$	$\phi_L = (0, 0)$ $\phi_R = (\frac{1}{4}, \frac{1}{4})$ $\Gamma^{8,0}(E_8) \leftrightarrow \Gamma^{8,0}(E_8)$ $V_L = (0^8; 0^8)$	4
		Model 4 on S^1, Coulomb branch		
20	Het	$2\Gamma^{2,2}(A_2) + 2\Gamma^{8,0}(E_8)$	$\phi_R = (\frac{1}{6}, \frac{1}{6})$ $\Gamma^{2,2}(A_2) \leftrightarrow \Gamma^{2,2}(A_2)$ $V_L = (0^8; 0^8)$	12
22	Het	$\Gamma^{4,4}(D_4) + 2\Gamma^{8,0}(E_8)$	$\phi_L = (0, 0)$ $\phi_R = (\frac{1}{2}, \frac{1}{2})$ $V_L = (0^8; 0^8)$	2
		Model $1, 2, 3$ on S^1, Coulomb branch		

More 5d models with no hypers ?

rank	type	lattice $+\Gamma^{1,1}$	twist	order
2	II	$\Gamma^{4,4}(D_4)$	$\phi_L = (\frac{1}{6}, \frac{3}{6})$ $\phi_R = (\frac{1}{4}, \frac{1}{4})$	12
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8	II	$\Gamma^{4,4}(D_4)$	$\phi_L = (\frac{1}{2}, 0)$ $\phi_R = (\frac{1}{4}, \frac{1}{4})$	4
12	Het	$2\Gamma^{2,2}(A_2) + 2\Gamma^{8,0}(E_8)$	$\phi_R = (\frac{1}{6}, \frac{1}{6})$ $\Gamma^{2,2}(A_2) \leftrightarrow \Gamma^{2,2}(A_2)$ $\Gamma^{8,0}(E_8) \leftrightarrow \Gamma^{8,0}(E_8)$ $V_L = (0^8; 0^8)$	12
14	Het	$\Gamma^{4,4}(D_4) + 2\Gamma^{8,0}(E_8)$	$\phi_L = (0, 0)$ $\phi_R = (\frac{1}{4}, \frac{1}{4})$ $\Gamma^{8,0}(E_8) \leftrightarrow \Gamma^{8,0}(E_8)$ $V_L = (0^8; 0^8)$	4
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22	Het	$\Gamma^{4,4}(D_4) + 2\Gamma^{8,0}(E_8)$	$\phi_L = (0, 0)$ $\phi_R = (\frac{1}{2}, \frac{1}{2})$ $V_L = (0^8; 0^8)$	2
		Model $1, 2, 3$ on S^1, Coulomb branch		

Observations

- Even Rank ?

More 5d models with no hypers ?

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12	Het	$2\Gamma^{2,2}(A_2) + 2\Gamma^{8,0}(E_8)$	$\phi_R = (\frac{1}{6}, \frac{1}{6})$ $\Gamma^{2,2}(A_2) \leftrightarrow \Gamma^{2,2}(A_2)$ $\Gamma^{8,0}(E_8) \leftrightarrow \Gamma^{8,0}(E_8)$ $V_L = (0^8; 0^8)$	12
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		Model $1, 2, 3$ on S^1, Coulomb branch		

Observations

- Even Rank ?

[Gkoumtoumis, Hull, Stemerdink, Vandoren 23']

- $r < 26 - d + 1$?

[Kim, HCT, Vafa 19']

More 5d models with no hypers ?

rank	type	lattice $+\Gamma^{1,1}$	twist	order
2	II	$\Gamma^{4,4}(D_4)$	$\phi_L = (\frac{1}{6}, \frac{3}{6})$ $\phi_R = (\frac{1}{4}, \frac{1}{4})$	12
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		Model 1, 2, 3 on S^1, Coulomb branch		

Observations

- Even Rank ?
- $r < 26 - d + 1$?

For H=0

- $r = 0??????$

[Mizoguchi 01']

More 5d models with no hypers ?

rank	type	lattice $+\Gamma^{1,1}$	twist	order
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		Model $1, 2, 3$ on S^1, Coulomb branch		

Observations

- Even Rank ?
- $r < 26 - d + 1$?
- $r = 0??????$

No scalars so not a perturbative string theory

More 5d models with no hypers ?

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8	II	$\Gamma^{4,4}(D_4)$	$\phi_L = (\frac{1}{2}, 0)$ $\phi_R = (\frac{1}{4}, \frac{1}{4})$	4
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		Model $1, 2, 3$ on S^1, Coulomb branch		

Observations

- Even Rank ?
- $r < 26 - d + 1$?
- $r = 0??????$

No scalars so not a perturbative string theory

Maybe strong coupling of 4d with one vector?

Abelian Orbifolds

Observations

- Even Rank ? ✓
- $r < 26 - d + 1$?
- $r = 0??????$

No scalars so not a perturbative string theory ✗

Maybe strong coupling of 4d with one vector? ✗

Abelian Orbifolds

Observations

- Even Rank ? ✓
- $r < 26 - d + 1$?
- $r = 0$??????

No scalars so not a perturbative string theory ✗

Maybe strong coupling of 4d with one vector? ✗

Maybe strong coupling of 3d with two vectors?

3d models with no hypers and two vectors

- Find 4d orbifold with untwisted sector: $(4\text{d }\mathcal{N}=2\text{ Gravity})+1(\text{Vector})$

3d models with no hypers and two vectors

- Find 4d orbifold with untwisted sector: $(4\text{d } \mathcal{N} = 2 \text{ Gravity}) + 1(\text{Vector})$
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Could this be our theory?

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[Lee, Lerche, Weigand 19']

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Emergent string conjecture: Infinite distance limit decompactifies or string limit

Two non-compact scalars: R_{S^1} and g_s

$R_{S^1} \to 0$: $\mathcal{N} > 2$

$R_{S^1} \to \infty$

$g_s \to \infty$: ?

We need to compute the instanton corrections

Abelian Orbifolds

- Choose the starting point: IIA, IIB, Heterotic

- Choose even self-dual lattice: $\Gamma^{D,D}(\mathfrak{g}) = \{(p_L, p_R) \,|\, p_L \in \Lambda_W(\mathfrak{g}), p_R \in \Lambda_W(\mathfrak{g}), p_L - p_R \in \Lambda_R(\mathfrak{g})\}$

$$\Gamma^{D,D}(\mathfrak{g}) + \Gamma^{16,0}(E_8 \times E_8)$$

Lattice Automorphisms/crystallographic symmetries of T^D

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Lattice Automorphisms/crystallographic symmetries of T^D

Are there such automorphisms that act crystallographically on $\Gamma^{D,D}$ but not T^D ?

Yes!

[Harvey, Moore, Vafa 87']

Quasicrystalline Compactifications

- Choose the starting point: IIA, IIB, Heterotic
- Find automorphisms that act crystallographically in $2d$ but not d
- Build even self-dual lattice $\Gamma^{D,D}$

Quasicrystalline Compactifications

Q	6d	$\Gamma^{4,4}$	Twist	Known
16	$1G + 21T$	$2\Gamma_C^{2,2}$	$\mathbb{Z}_{12} : \{1/12, 1/12\}, \{5/12, 5/12\}$	K3
8	$1G + 9T + 8V + 20H$	$\Gamma_C^{4,4}$	$\mathbb{Z}_{20} : \{1/20, 3/20\}, \{7/20, 9/20\}$	$CY3 \to dP9$

Freely Acting

Q	5d	Lat.$+\Gamma^{1,1}$	Twist
16	$1G + 1V$	$2\Gamma_C^{2,2}$	$\mathbb{Z}_{12} : \{1/12, 1/12\}, \{5/12, 5/12\}$
0	$1G + 4V + 2F + 3S_R$ $1G + 3V + 2S_R$ $1G + 3V + 2F + 2S_R$	$\Gamma_C^{4,4}$ $\Gamma_C^{4,4}$ $\Gamma_C^{4,4}$	$\mathbb{Z}_{20} : \{1/20, 3/20\}, \{7/20, 9/20\}$ $\mathbb{Z}_{30} : \{1/30, 11/30\}, \{7/30, 13/30\}$ $\mathbb{Z}_{30} : \{1/30, 7/30\}, \{11/30, 13/30\}$

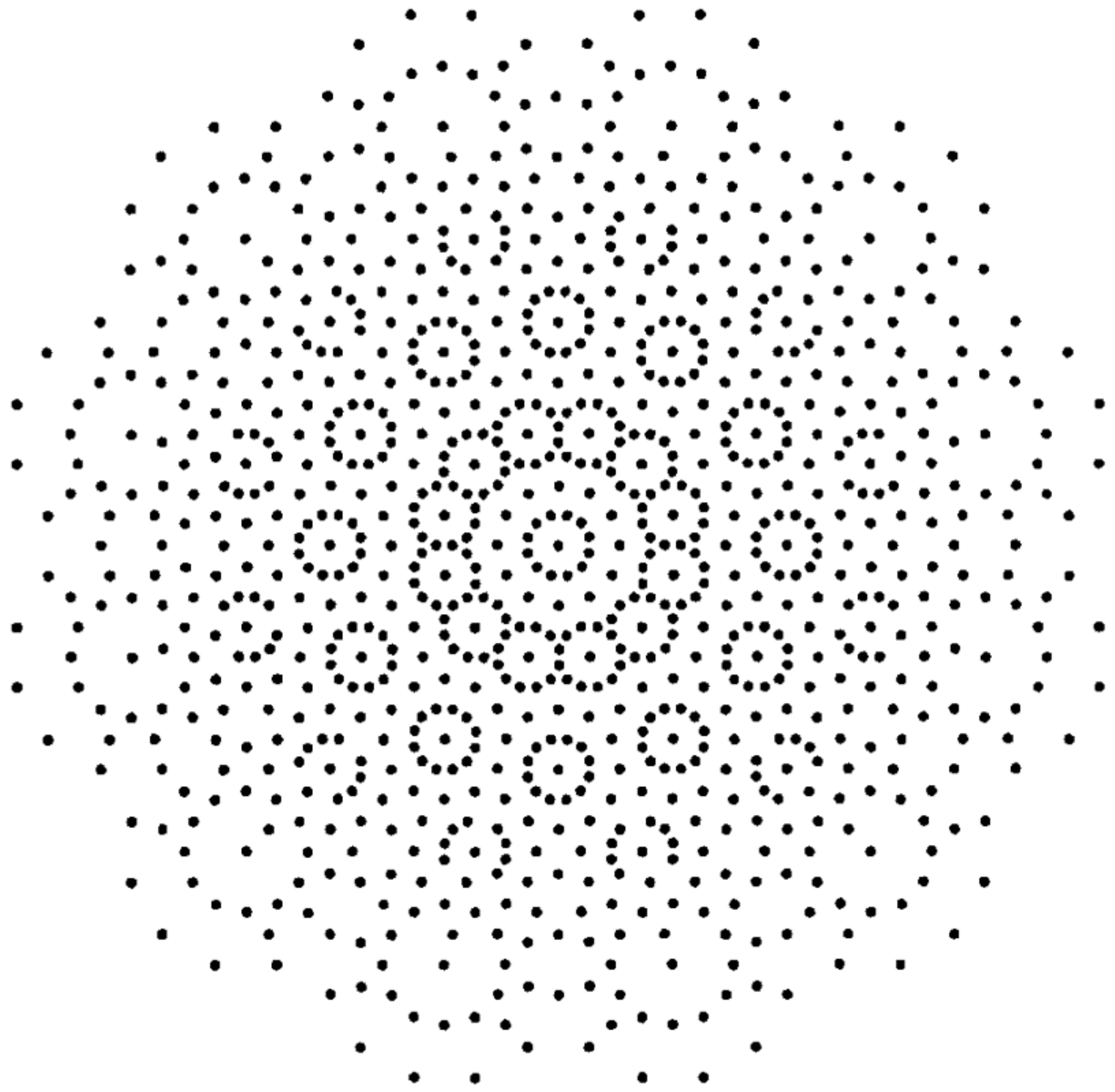
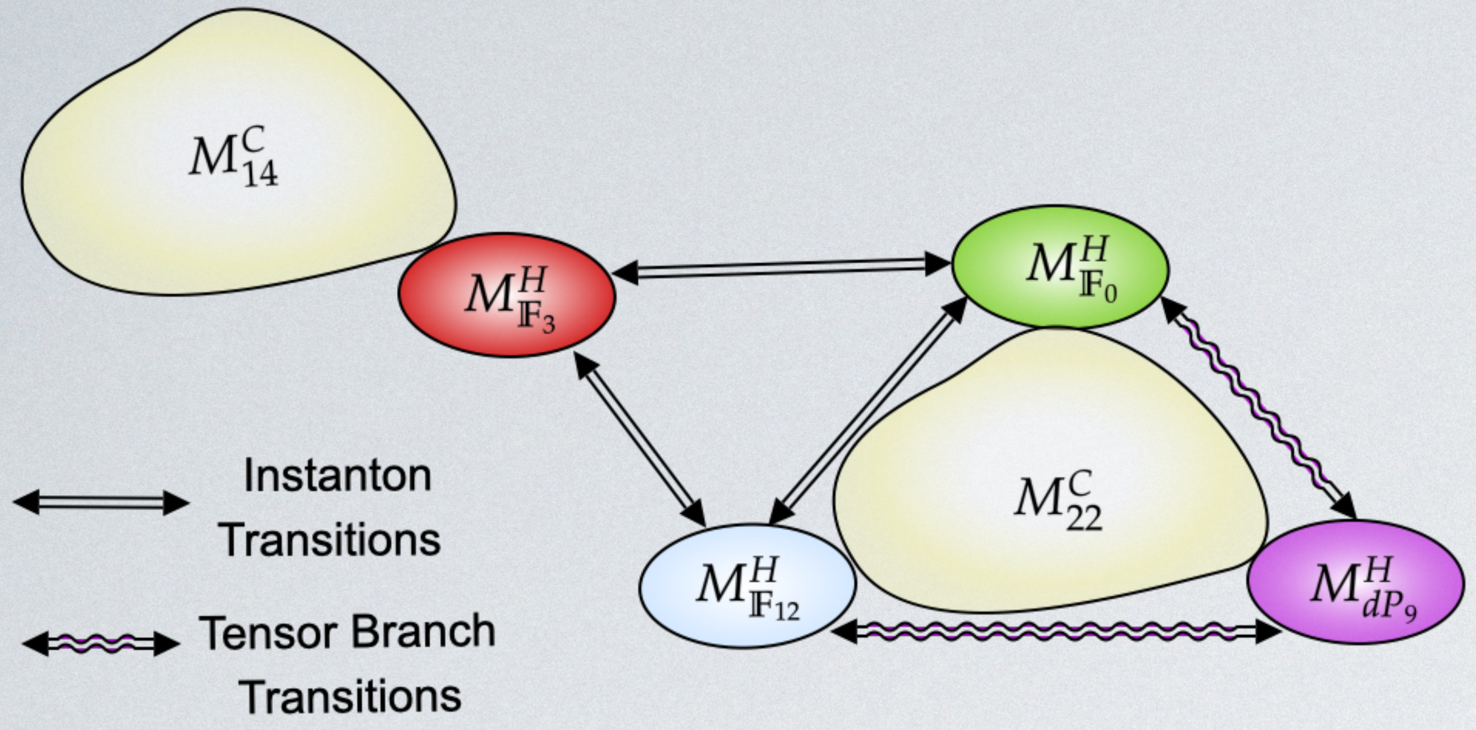


Fig. 1. p_L in the $\mathbf{Z}/12\mathbf{Z}$ quasicrystal for states with $p_L^2 + p_R^2 < 12$.



Summary and future direction

- **Non-geometric models**

Understanding the boundary of the string landscape

Where is the 5d $\mathcal{N}=1$? Compute corrections?

Good testing ground for Swampland conjectures

They kill moduli: important for realistic non-susy models

Other like $SO(16)\times SO(16)$ string theory?

- Any new ideas for non-geometric string constructions?

Thank you very much for listening!